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ADDITIVE MANUFACTURING (AM) IN EXPEDITIONARY OPERATIONS: CURRENT NEEDS, TECHNICAL CHALLENGES, AND OPPORTUNITIES

by

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June 2016

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Additive manufacturing (AM), or 3D printing, is poised to change the world of military expeditionary operations. It has the potential to affect every element of military operations—logistics, training, simulation, and warfighting. However, these cutting-edge technologies are shifting so rapidly that the current military acquisition system is not prepared for their adoption on a large scale. Among the issues that need to be addressed are 3D watermarking of digital models, proper prints in a distributed system, security of a repository of 3D models, and on-site customization of existing models. The author performed an empirical study centered around a survey of United States Marine Corps (USMC) and United States Navy (USN) personnel. The objective was to determine which of the promising 3D technologies have been adopted in United States Marine Corps and United States Navy and which should (or should not) be adopted. The survey and thesis conclude that AM and Contour Crafting have a lasting place in future USMC and Navy operations. Adoption of AM in the USMC and USN is still rare, but most agree that it can be used to great effect. The thesis recommends that more studies be performed to determine the best way forward for AM within the USMC and USN.

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ADDITIVE MANUFACTURING (AM) IN EXPEDITIONARY OPERATIONS: CURRENT NEEDS, TECHNICAL CHALLENGES, AND OPPORTUNITIES

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ABSTRACT

Additive manufacturing (AM), or 3D printing, is poised to change the world of military expeditionary operations. It has the potential to affect every element of military operations—logistics, training, simulation, and warfighting. However, these cutting-edge technologies are shifting so rapidly that the current military acquisition system is not prepared for their adoption on a large scale. Among the issues that need to be addressed are 3D watermarking of digital models, proper prints in a distributed system, security of a repository of 3D models, and on-site customization of existing models. The author performed an empirical study centered around a survey of United States Marine Corps (USMC) and United States Navy (USN) personnel. The objective was to determine which of the promising 3D technologies have been adopted in United States Marine Corps and United States Navy and which should (or should not) be adopted. The survey and thesis conclude that AM and Contour Crafting have a lasting place in future USMC and Navy operations. Adoption of AM in the USMC and USN is still rare, but most agree that it can be used to great effect. The thesis recommends that more studies be performed to determine the best way forward for AM within the USMC and USN.

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List of Acronyms and Abbreviations

3D	three dimensional
ABS	acrylonitrile butadiene styrene
AM	additive manufacturing
AI	artificial intelligence
BIM	building information modeling
CONOPS	Concept of Operations
COTS	commercial-off-the-shelf
CAD	computer-aided design
CC	Contour Crafting
CORE	Core Graphics System
DARPA	Defense Advanced Research Projects Agency
DOD	Department of Defense
X3D	Extensible 3D Graphics
FABLAB	Fabrication Laboratory
FOB	forward operating base
FDM	fused deposition modeling
GKS	Graphical Kernel System
HA/DR	humanitarian aid and disaster relief
IED	improvised explosive device
IP	intellectual property

IRB	Institutional Review Board
JFMCC	Joint Force Maritime Component Commander
JTF	Joint Task Force
LS-AM	large scale additive manufacturing
LOG-STO	logistics science and technology objectives
MOS	Military Occupational Specialty
MRL	manufacturing readiness levels
MJ	material jetting
MWTC	Mountain Warfare Training Center
NCCC	National Concrete Canoe Competition
NEC	Navy enlisted classification
NIST	National Institute of Standards and Technology
NPS	Naval Postgraduate School
ONR	Office of Naval Research
PII	personally identifiable information
PLA	polylactic acid
PBF	powder bed fusion
PHIGS	Programmer's Hierarchical Interactive Graphics System
ROMO	Range of Military Operations
SEA-STO	sea science and technology objectives
STO	science and technology objectives
SM	Smart Manufacturing

SLA stereolithography

TAM Technology Acceptance Model

TRL technology readiness levels

UV ultraviolet

USG United States Government

USMC United States Marine Corps

USN United States Navy

USC University of Southern California

VRML Virtual Reality Modeling Language

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Executive Summary

Additive manufacturing (AM), or 3D printing, has the potential to change the way that the USMC and USN operate across the range of military operations. This thesis evaluates many aspects of AM for military use with an emphasis on the diffusion of innovation within the USMC and USN. A survey was conducted, querying 120 Marines and Sailors. The results indicate that Marines and Sailors adopt technology for varying reasons including: leadership and peer endorsement, media advertisements, perceived ease of use and benefits of use, in addition to many other items discussed at length in the thesis. Contour Crafting is discussed with respect to its impacts on USMC and Navy operations in the asymmetric battle field. 3D model formats are also discussed with a focus on digital security, digital watermarking, digital twin, and the digital thread. This thesis concludes that it is highly likely that the military will face new and bigger challenges regarding 3D printing will be in the operational domain. Immense challenges will inevitably demand exploration of new ways of doing old tasks, necessitating a flexibility and ingenuity to address new demands and conduct new tasks that have never existed before. The distributed logistics system that will fully support expeditionary manufacturing and exemplifies a good way of dealing with future situations; the approach demonstrated here will allow the USMC to maintain the adaptability and cunning speed that has defined amphibious warfare throughout history.

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CHAPTER 1:
Introduction

1.1 Research Domain

The United States Navy (USN) and United States Marine Corps (USMC) pride themselves on being able to quickly and efficiently deploy to any location in the world in response to any need. The USMC and USN teams create initial order out of complete chaos. These chaotic events can be anything, from humanitarian aid and disaster relief (HA/DR) missions such as in Haiti in 2010 to a full strategic level combat operation such as the initial invasion of Iraq in 2003. The Marine Corps is known as the nation's expeditionary force in readiness. Throughout history, Marines and Sailors have shown that speed, cunning tactics, and battlefield innovations can succeed in creating order from chaos even amidst the most difficult and austere missions. In recent years, the speed with which technology and computing have evolved has dictated that both the Navy and Marine Corps rapidly improve their training, tactics, and procedures to keep the pace. One aspect of this lightning quick technology is additive manufacturing (AM), also known as three-dimensional (3D) printing. AM, if harnessed and employed correctly, enables our Marine Corps and Navy to not only get to the battle faster but also to arrive there with the capabilities and weapons to succeed. With AM, the Marine Corps can have the capability to innovate-in-place and build mission-specific equipment to suit whichever clime and place they find themselves in. Even though AM is currently an unproven yet highly promising technology, its time as a crucial aspect within Department of Defense (DOD) operations is fast approaching. In fact, AM may soon become one of the main staples in USMC / USN operations. The faster that broken weapons of war can be replaced, the faster wars can be won and order restored. By reducing logistical requirements and increasing the potential for at-sea and in-country innovation, AM implementation can help the USMC and USN create efficiencies and unit-level problem solving never before imagined on the asymmetric battlefield.

AM has changed from an abstract and fringe technology into one that will likely bring about the third industrial revolution [1]. Manufacturing is moving away from centralized, high cost entry systems to de-centralized and low-cost entry systems, such as desktop 3D

printers and scanners. Weapons and parts that once required a massive and expensive acquisition system to be produced can now be made in minutes or hours in the field or even in someone's home. AM has reached a point where anything from plastic and ceramic toys to ready-to-use metal parts for aerospace technologies and massive livable structures made of concrete are being printed daily.

In his top-level guidance to the entire Marine Corps, in FRAG-O 01/2016: Advance to Combat, General Robert B. Neller, the 37th commandant of the Marine Corps, states that:

> Innovation necessitates making hypotheses about the future operating environment that are then tested for validity, just as Marines did in the 1920s and 1930s. We may not find initial successes in all of our experimentation efforts, but our continued focus and persistence lead to solutions that enable our future force. This "disruptive" mindset must be pursued and fostered when found, or it will not sustain itself within our bureaucracy. We need creative leaders who think! [2]

General Neller highlights that; experimentation is key, and innovation is essential. In other words, the USMC and USN need to be ready to break things. His statement reveals that the Marine Corps and Navy need to operate more like a small startup and less like a large corporation. The Marine Corps and Navy must be ready to disrupt on all levels and also be ready to capitalize on potential benefits while identifying the pitfalls of pursuing such a untested technology. In his article, "Expeditionary Logistics for the 21st century: Tactical and Operational Efficiency," Lieutenant General Faulkner, Marine Corps, states that logisticians must become more adaptable, imaginative, and creative to solve logistics challenges inherent in our crisis response mission[s] and other operational requirements across the Range of Military Operations (ROMO) [3]. Additive manufacturing answers the call of both of these high-level charges from Marine leaders.

Navy leaders have been no different in directing the charge for innovation. In his December 15, 2015 memo to the Commandant of the Marine Corps and the Chief of Naval Operations, the Secretary of the Navy highlighted the need for innovation and flexibility:

> The Department of the Navy (DON) must rethink its approach to logistics in

> order to give the warfighting commander flexible options. The DON could benefit from incorporating advanced technologies such as advanced manufacturing, autonomous systems, and creative use of Adaptive Force Packages on existing and new platforms to transform our logistics concepts to a more agile, scalable warfighting tool. [4]

AM can give the Navy and USMC expeditionary construction mission increased speed and much needed flexibility.

Additive manufacturing is only a subset of a much larger system called Smart Manufacturing, or SM. This emerging field is defined by Davis et al. as "the dramatically intensified and pervasive application of networked information-based technologies throughout the manufacturing and supply chain enterprise." [5] In traditional manufacturing, a part is designed in two dimensions (blueprints), milled or constructed into its three-dimensional final self, and then used until its end of life. In contrast, SM uses a feedback system to monitor and provide understanding on all aspects of the parts during their creation, lifespan, and, when they are obsolete, SM generates a request for a new part or system. SM focuses on many aspects, including data analytics, data models, artificial intelligence (AI) processes, sustainable production, and networked sensors. AM serves a critical role in the SM process as it provides a force multiplier in the manufacturing cycle. AM is able to provide rapid prototyping, final part production, hybrid AM, [1] and lifecycle updates to parts that will be nothing short of revolutionary in the coming years.

1.1.1 United States Marine Corps (USMC) Mission

In the National Security Act of 1947, the mission of the present-day Marine Corps was defined and established. It says that, among other missions, Marines are to provide Fleet Marine Force with combined arms and supporting air components for service with the United States Fleet in the seizure or defense of advanced naval bases and for the conduct of such land operations as may be essential to the execution of naval campaign [6]. This first item of their mission implies that the Marines must be expeditious to their core. In order to seize advanced naval bases, the Marines must remain light and agile, adapting to changing conditions much more quickly and efficiently than the other armed services and

[1] Hybrid AM is to 3D print a mold for use with an injection molding type machine.

also the enemy. Compared to the Army, the Marine Corps is a shock force, used when speed coupled with specific force is needed, generally from the sea. The Army fills its traditional role, to amass a ground force. When the situation requires more speed and specific abilities, the Marine Corps is then deployed. The specific speed that both the Marines and Navy require couples well with the benefits that AM and SM can provide.

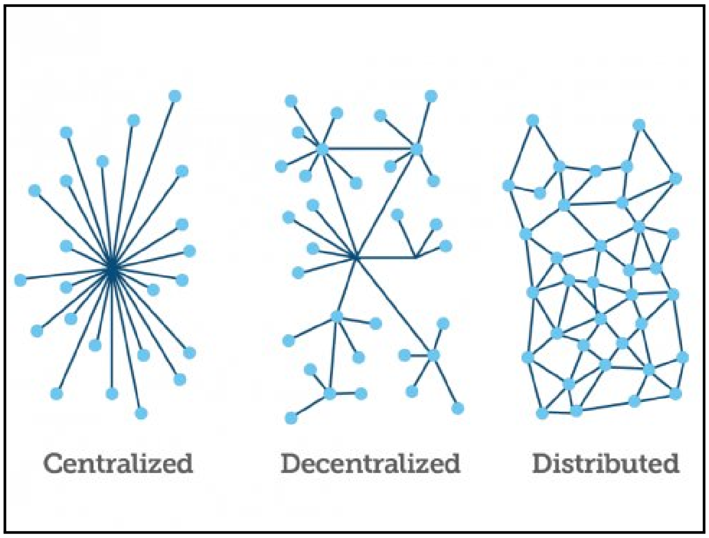

Figure 1.1: Centralized Logistics Is Compared here to Decentralized And Distributed Logistics. Source: [7]

Naval forces require logistics systems that are fluid and dynamic. With ships and missions positioned across the globe, a naval logistics system must have distributed logistical capabilities to ensure the right equipment and parts reach the right location and people. The USN currently employs a decentralized system. Figure 1.1 demonstrates both decentralized and distributed methods. The location that requires assistance may be based on a ship in the middle of the ocean or 300 miles inland at a Marine forward operating base (FOB). Units are usually equipped with the parts and supplies that they think (or know) are going to deteriorate during their assigned mission. Planning ahead enables the unit to fix equipment without having to rely on ordering a part from a distant location with a non-immediate lead time. Having the replacement part on hand enables a piece of equipment to be repaired quickly so that the unit can quickly return to its mission. The equipment being repaired can be anything from a Marine's rifle to an integral part of a Navy ship. AM can most benefit the USMC and Navy teams in parts repair and replacement, lessening or eliminating the need to wait for a replacement. AM gives our naval logistics system another tool for

creating tools that can help enable Sailors and Marines to get back in the fight.

AM can shorten the logistics trail that has followed warfighters through the ages, allowing the upkeep of equipment and vehicles nearing obsolescence. The USMC has several vehicles close to the end of their serviceable life that must remain in service for longer due to replacement systems' unavailability, risking lives. For example, the USMCs BV-206 has been in service since the mid-1980s, and it is meant to be used by units in cold weather climates [8]. This vehicle was procured with no program of record to acquire parts for maintenance and repair [8]. With no program of record to support the vehicles, units find it difficult to find and purchase parts. These parts are unavailable either because the company that usually manufactures them is no longer in business or simply because the parts are not in production. AM can help keep nearly obsolete vehicles going for longer while the replacements are fielded. Robert W. Appleton, a retired Marine Corps Master Gunnery Sergeant captures this concept:

> The benefits of AM to the Navy are plenty. The Navy and DoD are dealing with aging systems. Legacy systems are increasing in number and facing obsolescence. If a part breaks, we are faced with non-existent suppliers, unreliable foreign sources and unavailable drawings. In such a scenario[,] it is possible to reverse engineer the damaged part and have a replacement produced by AM. [9]

In a traditional part replacement process, for example, a truck breaks engine part X. The truck is brought back to a maintenance facility and evaluated. Once part X is identified, a replacement is sourced. If it cannot be sourced locally or regionally, a search goes out to see who has it and how long it will take to get there. If this standard process fails somehow, other means need to be used to get the truck back on the road. Perhaps part X can be bought through a third party such as eBay. If not, the part most likely needs to be manufactured at a great cost. Manufacturing is usually done by the original manufacturer. If the manufacturer is no longer willing or available to produce the part, the drawings for the original part need to be found and used to help build a new part. Here, AM can shorten this lengthy, costly, frustrating, and sometimes impossible process exponentially by producing the same part at a fraction of the cost and time. However, AM is not appropriate for all part replacement, as shown in Figure 1.2. In this example, the high initial cost of injection molding does not

make much sense for a small batch of parts but becomes more affordable per piece if larger batches are made [10]. While AM has a more fixed cost, current AM technology is still expensive for metal parts and does not make sense for parts that are needed often and can be made in bulk in a traditional manufacturing process.

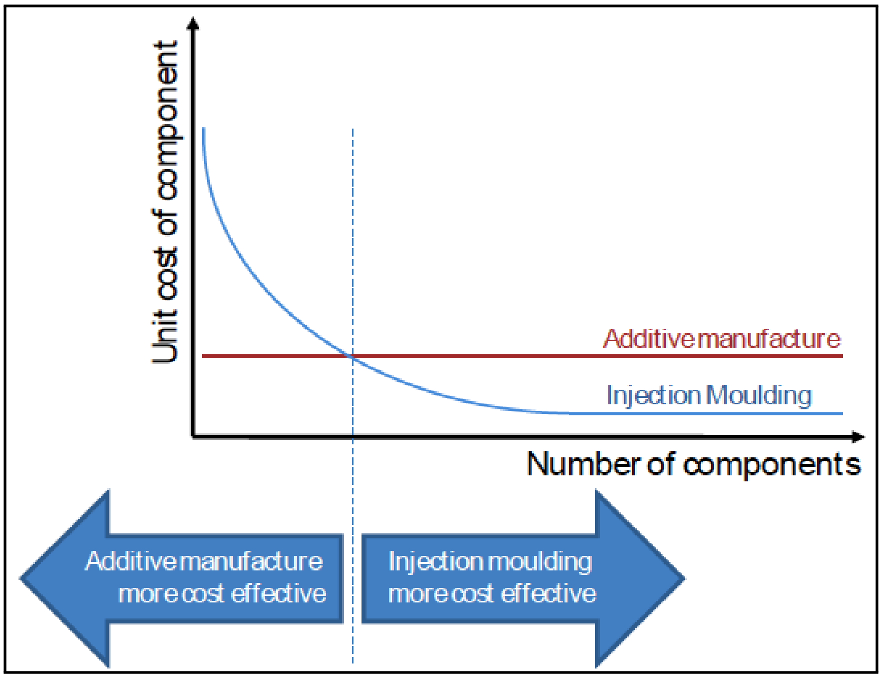

Figure 1.2: Here, AM Cost Is Compared with Traditional Manufacturing Techniques. Source: [10]

1.1.2 Large-Scale Adoption

The DOD is currently increasingly interested in AM and the pace of adoption. AM was brought to maturity in the late 1980s when it was used for rapid prototyping [11]. Currently, AM's ability to create low-cost, high-performance computing, coupled with expiring patents and more affordable 3D consumer grade printers has increased interest in its potential applications. In the past, the U.S. military was the innovator in most technological spaces. The DOD had the monetary resources and personnel to develop high-risk ideas and theories from the idea all the way to a final product. While the DOD's capacity for innovation remains true in most domains, it is quickly changing. The civil sector is now able to innovate at a pace that, in some cases, is out-pacing the DOD. Also, the current DOD acquisition process is cumbersome and elusive to most outsiders. A similarly bulky acquisition process

does not exist in the civil sector. When a private company wants to develop a new and promising technology, they do not need to worry about sourcing parts and equipment fairly and transparently to their suppliers. They are able to procure parts and services that they deem to be the most beneficial to whatever technology they are developing.

With civilian innovation coming to maturity at an ever-increasing pace, we may find (and, in some cases, do find) the military looking to civil industry to help with the adoption of new technology. The USMC has the highest percentage of young people among all of the armed services. According to Marine Corps Community Services, 61% of Marines are 25 or younger [12], lending strength to the adoption and acceptance of new technologies. The Pew Research Center reports that younger adults are more likely to have game consoles, current cell phone technology, and tablet computing devices [13]. It makes sense to look to our younger men and women in uniform to better gauge how and why Marines and Sailors are using new and emerging technology such as AM or 3D printing. Alternatively, if Marines and Sailors are not currently using AM, how can they be better prepared for its adoption?

1.1.3 Gartner Hype Curve

Three dimensional printing has taken a significant amount of time to come into mainstream vocabulary. USMC and USN leaders need to be able to identify what technology is oversold. The Gartner Hype Curve (Figure 1.3) shows how 3D printing is staring to reach a plateau of productivity. Some aspects of 3D printing, such as 3D printing of prototypes, have reached the point where expectations of the technology are plateauing and productivity is proven (Figure 1.3). Not so for 3D printing in the supply chain. It is interesting and holds much promise, but in the vast majority of manufacturing examples, 3D printing is a hard business case to make. When supplies and parts are hard to come by, such as on a ship or at a FOB, the business case becomes easier to prove. Rather than being a hype technology in the USMC and USN, AM may well be a force multiplier.

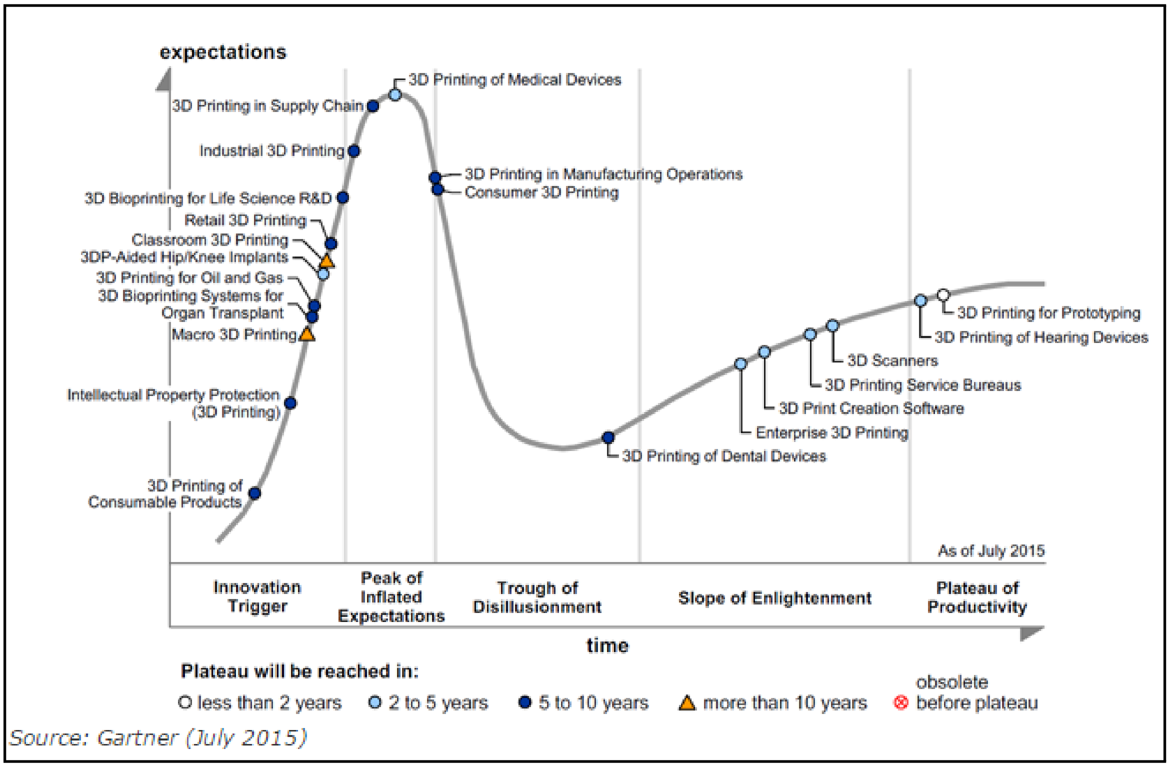

Figure 1.3: 2015 Gartner 3D Printing Hype Curve Looks at Technologies That Are Either in a Hype Phase or in a Productivity Phase. Source: [7]

1.2 Research Problem and Motivation

The USMC and USN communities currently have a small cadre of AM professionals in various offices and branches. Support for AM investment in training and logistics increases daily, showing that both researchers and strategists think AM can have a game-changing impact on operations, tactics, and logistics. Gen. Robert H. Barrow, former commandant of the Marine Corps, noted in 1980 that "amateurs talk about tactics, but professionals study logistics" [14]. In logistics, AM has the greatest impact in USMC future combat operations. AM allows fighting forces to arrive to the battle faster, and better equipped, and with a more robust and agile force to carry on any given operation.

Adapting AM into USMC and USN operations allows for the reduction in logistics convoys, which, in turn, reduces lives lost. Every convoy, for example, that is not executed, means lives saved. A 2009 report from the Army Environmental Policy Institute found that, in

Afghanistan, for every 24 convoys, one expects, on average, one casualty [15]. If convoys are not on the roads as often supplying everyday mundane parts and equipment, lives are saved.

With current state of the art AM machines, the question to be asked by both services is not what can be printed, but what should be printed. This holds true for both sea-based and expeditionary land operations. If the USMC and USN use AM, what set of approaches should be adopted and practiced? AM is still a relatively expensive manufacturing system, so everything cannot be made with the technology, however, some things can and should be made. Adopting AM enables personnel with little or no experience to produce parts simply by turning on and maintaining an AM machine. Personnel need to know only how to maintain the AM machine. The engineering experts who build and design the 3D models to be printed are centralized at another location. If the part is incorrect or it needs customization, feedback is sent back to the engineering experts for redesign and reprinting on site. This takes place aboard ship or at a forward operating base FOB. Experts and engineers become centralized; doers and builders become distributed.

The 2012 USMC Science and Technology Strategic Plan identifies science and technology objectives (STO) that define "technology capability enhancements most needed to enable the warfighting capabilities of our future operating forces" [16]. Being a possible logistical force multiplier, AM fits into LOG-STO-2 particularly well:

> Asset versatility simplifies logistics. Its provided by ensuring that technologies incorporated in future versions of basic inventoried items serve to expand Warfighter flexibility in adapting to a broad range of potential operational environments. Technologies consistent with three design concepts (scalable modularity, functional modularity and transport modularity) may be particularly beneficial. [16]

AM can potentially effect all three of the modularities listed above, underscoring its potential in the future force. Another applicable STO is SEA-STO-14. It calls for, "improved manufacturing technologies. In partnership with industry, develop manufacturing technologies and composite material uses that lead to reduced construction and lower life cycle maintenance costs." [16] AM fits nicely: it has a potential to use composite material to significantly reduce construction cost and lower life cycle maintenance costs. This is true for not only small replacement parts, but also for the construction of occupy-able structures through the use of Contour Crafting (CC).

1.3 Research Questions

The questions here are the essential elements to research in this domain:

- Does additive manufacturing have the ability to significantly add to the capability of the Marine Corps? If so, what elements of digital thread need to be addressed if additive manufacturing technologies are to be fully integrated in USMC operations?
- Further, what type of scenarios and use cases will benefit most from the application of additive manufacturing?
- Then, what are the technical issues, user attitudes, and domain characteristics that may positively or adversely influence adoption of additive manufacturing in the USMC?

1.4 Scope

Via query and analysis, this thesis examines the USMC and USN for insights into how and why their members are using or will use technology, and, more specifically, how they would use AM. The thesis also examines current AM technological trends and advancements and how AM technologies can benefit USMC and USN operations.

The best way to acquire thorough information would be to query the entire active duty naval force. That, however, was out of scope for the conduct of this thesis. Instead, this thesis examines several specific USMC and USN units deemed to have the most applicability to use current AM technologies. The initial analysis suggested that the USMC and USN engineers are most affected by AM and CC. Upon further investigation, it was discovered that many communities in the USMC will benefit from a study of AM uses. The study was then broadened to include other USMC units.

1.5 Thesis Contributions

This thesis benefits the U.S. Navy and Marine Corps as a comprehensive investigation of potential substantial savings brought by AM technologies and approaches through reduction of errors, reduction in waste, increased operational readiness, increased precision in execution of logistic operations, and also potential savings through reduced manning. It is hypothesized that multiple synergies will be found between Marine Corps and other DOD services, and that many elements of this research will directly be applicable to the rest of DOD. Further, the research on AM will also result in direct applicability for the civilian domain.

1.6 Thesis Structure

Following the current introduction in Chapter I. Chapter II provides a detailed background of the topics. Chapter III then investigates the current state of the art of the AM industry. Chapter IV provides and detailed look into the diffusion of technological innovations across a populous. Chapter V details several specific case studies of CC and current USMC and USN AM initiatives. Chapter VI describes the survey results of the study conducted in support of this thesis. Chapter VII lists and discusses the survey data. Chapter VIII concludes and summarizes the research, giving recommendations for AM incorporation into the USMC and USN.

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CHAPTER 2:
Background

2.1 Additive Manufacturing (AM)

Much work has been done over the past three decades in the field of AM. AM, as we know it today, entered the mainstream in the late 1980s with the inventions of Chuck Hull [17]. Hull invented and patented what is now called stereolithography (SLA); "SLA greatly reduced the time it takes for designers and engineers to create a concept design or functional 3D prototype" [17]. Rapid prototyping is how AM first gained a foothold as an emerging technology. Before AM, a prototype would take anywhere from several weeks to several months to build. Any modifications to that specific prototype would again take weeks or months before another prototype could be built and delivered. Today, AM is no longer a simple device used solely for rapid prototyping. Today, AM is a developing system able to manufacture aerospace grade parts for use on commercial high tech aircraft such as the Boeing 787 [9] and the Space X Superdraco thrusters [18].

2.1.1 Small and Medium-Scale Additive Manufacturing

Small and medium-scale AM has grown exponentially over the past 20 years from early rapid prototyping to current printing of final manufactured parts. Of particular interest is the growth of AM machines priced at less than 5000 USD. [19] In 2015 alone, sales of printers priced in this category grew 70%. Over the past 26 years, the AM industry as a whole has grown by 26.2% [20]. Metal printing through AM is also starting to explode with companies such as General Electric printing parts for use in their jet engines. According to Wholers [21], in 2015, companies purchased 808 machines capable of building metal parts layer by layer, up from 550 in 2014 and 353 in 2013. This means that more and more companies are investing significantly in AM machines capable of producing final production parts.

2.1.2 Contour Crafting with Concrete for AM

Contour Crafting (CC) is not a new idea but is one that is gaining popularity and interest [22]. CC is the construction of structures and buildings using the same basic techniques as small and medium scale AM. Some CC techniques use a basic extruding method and build a structure by layering concrete. Other techniques involve printing the skeleton of the structure and filling the skeleton with foam or filler. The basic idea of CC is very similar to how a barn or cliff swallow builds its nest; take, for example, the description provided by the Cornell Lab of Ornithology:

> Swallows gather mud in their bills along streambanks, lakesides, or puddles, usually near the colony but sometimes up to a few miles distant. They bring mud pellets back in their bills and mold them into place with a shaking motion. The finished nest is gourd shaped and contains 900–1,200 individual mud pellets. It measures about 8 inches long, 6 inches wide and 4.5 inches high, with walls 0.2–0.7 inches thick. [23]

CC uses the same basic principle. B. Khoshnevis et al. tells us that "a common limitation associated with most current layered fabrication methods is the maximum size of the component that can be fabricated generally not larger than a meter in any dimension" [22]. In CC, size is not a factor. Buildings large enough to live in have been built using methods such as CC. With CC, concrete is extruded through a patented nozzle system to print a building layer by layer. Using CC, buildings and structures that would normally take months to complete, generating tons of waste, a similar structure can be produced in as little as 20 hours with zero residual waste.

2.1.3 Additive Manufacturing within Smart Manufacturing

Smart Manufacturing (SM) is an emerging method of efficient building and management of digital and physical objects. The National Institute of Standards and Technology (NIST) defines SM as systems that are “fully-integrated, collaborative manufacturing systems that respond in real time to meet changing demands and conditions in the factory, in the supply network, and in customer needs” [24]. SM is the next evolution of the digital age. Cheap, high-performance computing coupled with artificial intelligence (AI) and AM, among other

things, will enable manufacturing systems to reach higher levels of efficiency and waste reduction [5]. Davis et al. goes on to further clarify SM as "the dramatically intensified and pervasive application of networked information-based technologies throughout the manufacturing and supply chain enterprise. The defining technical threads are time, synchronization, integrated performance metrics and cyber-physical–workforce requirements." [5] The coming revolution in SM has the potential to bring about a radical shift in how things are manufactured, maintained, and replaced. It is imperative that the USMC and USN keep abreast of SM as a larger system, along with a special focus on one particular subset, the focus of this thesis, AM.

2.1.4 Building Information Modeling

Coupling SM with CC, building information modeling (BIM) becomes very important to the life-cycle management of structures. Azhar describes BIM capabilities:

> "With BIM technology, an accurate virtual model of a building is digitally constructed. This model, known as a building information model, can be used for planning, design, construction, and operation of the facility. It helps architects, engineers, and constructors visualize what is to be built in a simulated environment to identify any potential design, construction, or operational issues" [25].

Using BIM, organizations are able to model a structure constantly throughout its life-cycle, from idea conception through construction, maintenance, and demolition. BIM will thus be an important aspect of SM and CC. As shown in a study by Azhar in 2011 covering four projects injected with the use of BIM, the monetary benefit from including BIM methodologies ranged from a low of 15,000 USD to almost 2,000,000 USD. [25] BIM, therefore, will potentially couple very well with the idea of CC.

2.2 Manufacturing Readiness Levels and Technology Readiness Levels

The DOD must constantly evaluate new and emerging technologies for relevance and importance to the U.S. Armed Forces. Failure to evaluate new and emerging technologies

quickly and efficiently could result in terrible and graphic defeats on a future battlefield. Known today as technology readiness levels (TRL)s were first introduced by NASA in the late 1980s. [26] Properly gauging maturity of technologies gives the DOD information about the resources that may be needed to bring these technologies to full maturation and deploy them into service. As shown in Figure 2.1, system with a low TRL level would require much greater effort to bring it to full maturity than a system with a higher TRL level.

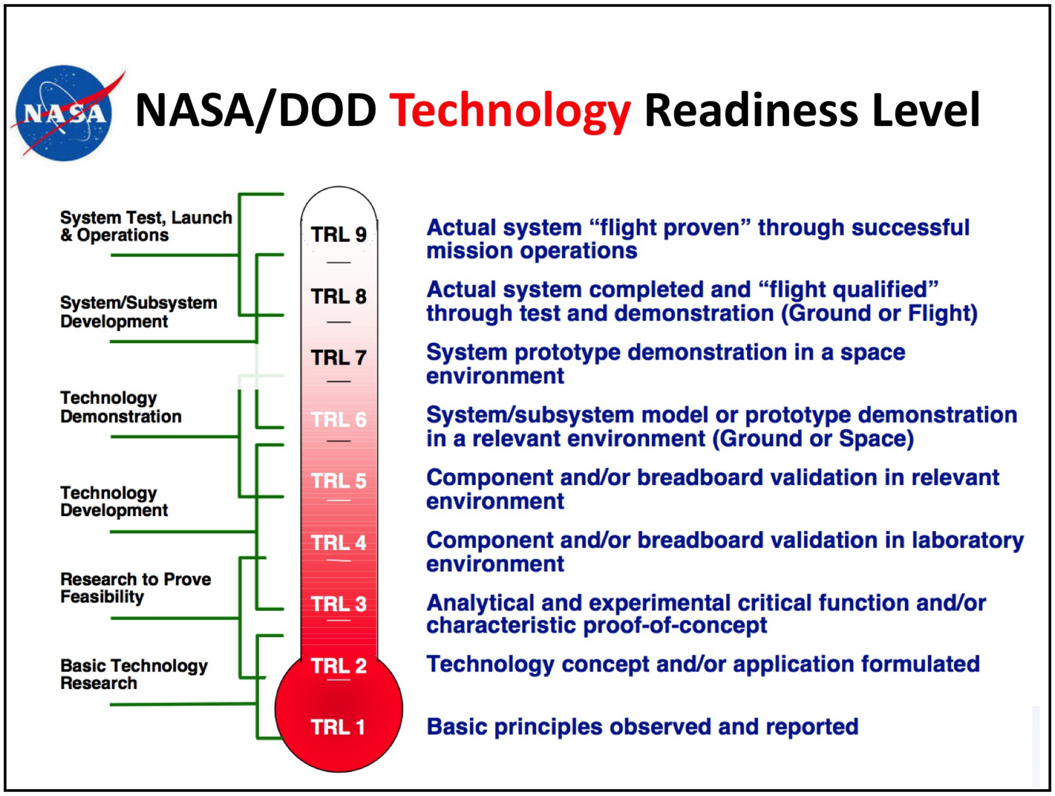

Figure 2.1: Technology Readiness Levels Illustrated, Ranging from TRL 1 (low) to TRL 9 (high). Source: [10]

TRLs are important in any conversation regarding new and emerging technologies such as AM and especially with CC. The USMC and USN must use the TRL definition for not only hardware and software systems but with the materials involved with AM and CC.

2.3 Current State of AM in USMC and USN

The applicability of AM and CC processes in the military could similarly impact warfare as did the invention of aircraft in the early 20th century. The possibility exists to significantly

shorten long and complicated logistics lines that stretch around the world. Hypothetically, a need could be produced at the point of need. Incorporation of AM into operations continues to increase. In March 2016, the USN and Lockheed Martin successfully launched a Trident II D5 Missile with an important cable cover made with AM and "digital manufacturing." [27] Having the AM-produced cover enabled the Navy and Lockheed Martin team to shorten their development time and bring a replacement part to service without the traditional waste and cost.

The USN is taking an interesting approach to the fielding and incorporation of AM into operations. The traditional and expected incorporation of new technology in a large organization, such as the Navy, is from the top down. The Navy is taking steps to see where AM could and should be incorporated into fleet logistics. In 2015, the Office of Naval Research (ONR) detailed their plan to further investigate AM and where within the Navy to exploit its benefits. [27] Jennifer Wolk, the Naval Surface Warfare Center Additive Manufacturing Lead, states: "additive manufacturing has the potential to be a disruptive technology and shows great promise for supporting Naval Sea Systems applications." [27] The Navy is also undertaking several studies to find out how current systems can be augmented by AM. Funded by the USN and Defense Advanced Research Projects Agency (DARPA), 3D Systems is investigating the use of direct metal printing where final usable metal parts are printed and used on current systems. [28] "The goal of the partnership is to continue to advance and develop the creation of high-resolution DMP technology and to provide training using 3DS's existing DMP technology for use by the U.S. defense and aerospace companies." [28] The Navy's top down approach, coupled with partnerships with industry, enable a solid footing for AM incorporation into the fleet.

On the opposite end of the spectrum, in a more bottom up approach that looks more like the recent maker movement [29], the Navy has funded and fielded several Fabrication Laboratories or FABLABs. These FABLABs are designed to let Sailors think, design, and build their solutions to fleet problems. [30] The Navy's intent with the FABLABS is to encourage low level solutions from those actually fixing the parts and systems. The USMC also has plans to incorporate a similar program called Expeditionary Manufacturing or EXMAN project. [31] The EXMAN project is very similar to the FABLAB initiative and will place 3D printers and other building systems in the hands of Marines. [31] This push for innovation at the lower level, coupled with the push for innovation from the higher level

makes the Navy very adaptable to AM as an emerging and promising technology.

2.4 Diffusion of Innovation

This section describes the diffusion of innovation, highlights its importance when looking at current AM technologies in the USMC and USN, and outlines possible problems with AM application in any large organization.

The diffusion of innovation is a much talked about and investigated aspect of new and emerging technologies. It was first brought to light by Everett Rogers in his 1962 book titled *Diffusion of Innovations*. Rogers elaborates how the adoption of all new technologies or ideas forms a traditional bell curve with individuals falling into one of five different categories: innovators, early adopters, early majority, late majority, and laggards [32]. He also breaks up diffusion into four defining elements: "...diffusion as the process by which (1) an innovation (2) is communicated through certain channels (3) over time (4) among the members of a social system. The four main elements are the innovation, communication channels, time, and the social system." [32]

Even though Everett Rogers is considered the father of innovation diffusion theory, he is not the only one who has attempted to decipher how and why people adopt innovations. One such study in 1989 took a look at user acceptance of new computer systems; F. Davis of the University of Michigan hypothesized that perceived ease of use and perceived usefulness were important aspects of the adoption of computers, a growing technology at that time. [33] Davis wanted to see if he could determine "better measures for predicting and explaining use." [33] One interesting focal point of Davis's work is the cost-benefit paradigm. He talks about a "cognitive trade-off between the effort required to employ the strategy and the quality (accuracy) of the resulting decision." [33] The author suggests that, in general, ease of use coupled with perceived benefit to user will result in a positive relationship with its adoption rate. [33]

Much work was done during the 1990s and early 2000s in the adoption of technology field. One study, focused on the adoption of south Indian rice growing technology, found that: "the results indicate that a lack of precise knowledge of the new technology was primarily responsible for the differences between the actual and maximum possible efficient outputs." [34] So, if people do not know about a technology or are not fully aware of its

benefits, they will be less likely to adopt it, confirming Everett Rogers findings in 1962. [32] In another study reported in 2002, researchers focused on faculty adoption of technology, and they found several important barriers as demonstrated in Figure 2.2.

Problems Reported by Faculty Members

Problem	Frequency of Faculty Reporting
Equipment failure or malfunction	37 (29.6%)*
Time to learn new technology	18 (14.4%)*
Carts too hard to use; don't like carts	11 (8.8%)*
Equipment too different across classrooms	11 (8.8%)*
Campus support weak	11 (8.8%)*
Software out of date	10 (8.0%)*
Takes too long to learn given value to learning	9 (7.2%)*
Software incompatible with classroom/office/ students' systems	6 (4.8%)**
Difficult to schedule classrooms with technology	6 (4.8%)**
Nowhere to learn; need to learn	6 (4.8%)**
Domain too slow	5 (4.0%)**
VIS screwed up[9]	5 (4.0%)**
Software malfunction	5 (4.0%)**
Light bulb burned out	5 (4.0%)**

* 99% confidence interval did not include 0
** 95% confidence interval did not include 0

Figure 2.2: Barriers to Technology Adoption as Identified by Teachers Using New Technology. Source: [35]

Among the problems listed in Figure 2.2, the time its takes to learn a new technology shows up both the number 2 and number 7 top problems, falling just behind new technology equipment reliability. With any new technology, it appears that the communication of the technologies' usefulness, perceived usefulness, and ease of learning the new technology are critical factors.

A user study focused on adoption of computer-supported training simulations in the military domain showed a surprising finding: "users in all groups were very receptive towards the idea of using training simulations. The most frequent reason for not using some training simulation was the fact that units did not know about the existence of the training simulation at all." [36], [37] Contrasting Yates and Sadagic's study with Davis's study, it seems that potential adopters may not know about a promising technology, let alone know about

its usefulness, and, in such cases, they cannot possibly adopt it. It may confirm that more assertive advertisement and information dissemination of technology is an important ingredient of successful diffusion of innovations.

Being government entities, the USMC and USN tend to adopt new and emerging technologies at a different pace than that of their civilian organization counterparts. Recently, in contrast to previous decades, the civilian sector is innovating at a faster pace than the government or military, and the government or military must adjust to keep pace. Michael Mintrom, also of Michigan State University, conducted a study to find out how what he calls "Policy entrepreneurs" influence the diffusion of innovation within their organization [38]. Both the USMC and USN are large organizations, so who drives innovations is of particular interest. In his study, Mintrom hypothesizes that: "Policy entrepreneurs constitute an identifiable class of political actors. Their presence and actions can significantly raise the probability of legislative consideration and approval of policy innovations." [38] This is very similar to the opinion leaders mentioned by Everett Rodgers in 1962. [32] Even though the focus of Roger's study is the state level, it is still very applicable to the federal level. Mintrom looks at the idea of enabling a parent to choose their child's school over being assigned to a school based on their home's location, referring to this as "school choice", and he concludes that: "policy entrepreneurs play an important role in articulating innovative ideas onto government agendas. They work hard at developing close ties with people through whom they can realize their policy goals[,] and they seek to develop convincing arguments for selling their policy ideas." [38] Not only does advertisement and information dissemination regarding the usefulness of a new and emerging technology increase its chance of adoption, having a policy entrepreneur lobbying for the technology within the government body is an important aspect, too.

2.5 Chapter Summary

AM and CC have the potential to disrupt not only the civilian sectors logistics flow but also to disrupt the way the DOD operates its logistics. With both the USMC and USN currently pursuing basic to advanced AM technology, a study must be performed to better inform leaders on the current state of technology adoption in the USMC and USN. The current state of AM adoption and acceptance in the USMC and USN is an important aspect of how and when the adoption of AM and AM policy will take place or has taken place and thus

allows military leaders to be prepared.

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CHAPTER 3:
Additive Manufacturing (AM)

3.1 Introduction

The act of making has been ingrained in the human experience for millions of years. Turning one thing into another more useful thing is what carries our species and has allowed us to survive. See Figure 3.1. "The appearance of the first intentionally modified stone tools over 2.5 million years ago marked a watershed in human evolutionary history, expanding the human adaptive niche and initiating a trend of technological elaboration that continues to the present day." [39]

Figure 3.1: Early Human Tool Making - An Example of Subtractive Manufacturing. Source: [40]

AM and CC processes can very simply modify an object to create a tool that can better solve a problem. Humans are not the only Earth-bound species to modify objects into other objects to better benefit the species. As mentioned in Chapter II, cliff swallows build their nests out of thousands of beak fulls of mud that then dry and form the structure of their nest. [23] Also, ants are particularly skilled at using grains of dirt to build their colonies or smaller, detached structures, piece by piece out of materials they source near their intended build site. They then place or push each grain into its intended location. [41] This simple act

has profound effects for the colony as a whole. Where there was not a habitable structure, now one exists. AM and CC are no different. They both simply turn one object (material) into a more useful one.

3.1.1 Bits to Atoms, Atoms to Bits

"The revolution is not additive versus subtractive manufacturing; it is the ability to turn data into things and things into data," says Neil Gershenfeld [42].

Many AM processes begin with computer based 3D models. These models are usually generated on a computer-aided design (CAD) software program and then converted to the industry accepted .STL file format as in Figure 3.2. The STL file contains data on many triangles that form together to make a full object in 3D (non-negative) space. Once the SLT file is built, a G-Code is generated from the STL to slice the 3D object into thin layers from the top down. Those slices are further reduced to coordinates so that the 3D printer knows where, when, and how to move while laying down material. An example of a G-Code file is shown in Figure 3.3 where X,Y and Z coordinates can be clearly read along with the letter E which stands for extrusion of the material.

```
solid name
    facet normal n_i n_j n_k
        outer loop
            vertex v1 v1 v1
            vertex v2 v2 v2
            vertex v3 v3 v3
        endloop
    endfacet
endsolid name
```

Figure 3.2: STL Code Is Commonly Used for 3D Printing It Includes Geometry Definitions but not Color Information. Source: [43]

The technology also exists to bring a physical part into the digital world for manipulation repair or data-basing. This is called 3D scanning. There are several techniques based around two ideas, scanning the entire exterior of an object or taking x-ray slices of the

```
;Sliced at: Mon 18-04-2016 10:20:23
;Basic settings: Layer height: 0.2 Walls: 0.7 Fill: 15
;Print time: 49 minutes
;other temp:210
;ideal temp:210
G90        ;absolute positioning
G92 E0                  ;zero the extruded length again
G0 F3000

;Layer count: 79
;LAYER:0
M107
G0 F3000 X16.195 Y31.386 Z0.260
G0 X16.021 Y31.499
;TYPE:SKIRT
G1 F300 X16.195 Y31.386 E0.00785
G1 X16.964 Y30.987 E0.04063
G1 X17.267 Y30.861 E0.05304
G1 X18.289 Y30.565 E0.09330
G1 X19.200 Y30.485 E0.12790
G1 X19.527 Y30.460 E0.14030
G1 X20.708 Y30.589 E0.18525
G1 X21.702 Y30.905 E0.22471
```

Figure 3.3: G-Code Example, From a 3D Model Made by the Author, Shows Positions for the 3D Printer Along with How Much Material to Place.

object and then assembling those x-rays to form a digital 3D model similar to a medical computed tomography or CT scan [44].

3.2 Smart Manufacturing

Smart manufacturing or digital manufacturing is a very recent concept brought about by the rise of high performance computers coupled with more and more manufacturing systems becoming automated and the free flow of accessible and shared data. SM is able to "adapt to new situations by using real-time data for intelligent decision-making." [45] SM's simple but potentially ground-breaking ability to manufacture in real time with constant feedback throughout the manufacturing process enables an organization to maintain an immense amount of flexibility and adaptability that the traditional manufacturing process lacks. "Design and production will become a computer supported and cooperative work of many dispersed and specialized groups," according to Kim et al. [46]. Modeling and simulation is used in concert with 3D model design and manipulation. Through digital manufacturing, waste is reduced and efficiencies are more easily and more frequently realized. For the USMC or USN operations, SM has the potential to enable faster repair and more efficient use of resources over the distributed defense domain. Davis stated that:

> Smart Manufacturing responds and leads to a dramatic and fundamental business transformation to demand-dynamic economics keyed on customers, partners and the public; enterprise performance and variability management; real-time integrated computational materials engineering and rapid qualification, demand-driven supply chain services; and broad-based workforce involvement. [5]

3.3 History of Additive Manufacturing

Many of today's AM methods were developed and refined over the last 150 years and summarized in Figure B.1. The earliest traceable idea of stacking two dimensional items on top of each other to form a three dimensional object was Blanthar in 1890, who patented an idea to construct three dimensional contour maps [47]. In 1860, François Willème extensively photographed objects and people, then used the profile generated from the many photos to sculpt a 3D model see(Figure 3.4). After the images were taken, a sculptor only sculpted 1/24 of the object then moved onto the next 1/24 slice [48].

In 1935, Isao Morioka of Japan filed a U.S. patent to blend topography modeling and photo-sculpture modeling to use "structured light (black and white bands of light) to photographically create contour lines of an object. The contour lines could then be developed into sheets and then cut and stacked or projected onto stock material for carving." [49] While these early examples of AM more resemble traditional subtractive manufacturing methods than the AM methods currently in use, the early methods stand as precursors for today's 3D printing.

Thirty years later, in 1956, Otto John Munz patented a system that closely resembles modern day SLA techniques [50], [47]. Figure 3.5 shows elements of Munz's work that are very familiar to current AM techniques. For example, below the build plate is an electric motor to lift the bin of a "a photosensitive medium." [50] The solidification of the medium was done, at the time, with a cathode ray tube similar to today's ultraviolet and light emitting diode (LED) light sources.

Steady progress through slow, incremental steps largely defined AM's evolution from its earlier days; in the late 1980s, however, Chuck Hull stepped in and forever changed the

Figure 3.4: Multiple Angles of Dr. Willeme's Photo-Sculpture Apparatus Used to Produce 3D Clay Models. Source: [48]

pace. In 1990, Hull patented his "method for production of three-dimensional objects by stereolithography (SLA)." [11] He was also a founder of the company 3D Systems, the company that is credited with developing SLA and the STL file format. 3D Systems is one of two major AM companies in the U.S., the other being Stratasys, also formed in the late 1980s by Scott Crump. At the time, Crump patented his idea for fused deposition modeling (FDM) [51]. He serendipitously came across this idea when making a toy frog for his daughter with a hot glue gun [51]. Since their key innovations, 3D Systems and Stratasys have traditionally made very high end, high precision AM machines for large organizations who can typically afford the machines that can range anywhere from 500,000 USD to over one million USD [21]. While AM production and methods have continued to evolve, the pace quickening, one interesting example of information and technology dissemination came about with the desktop maker movement.

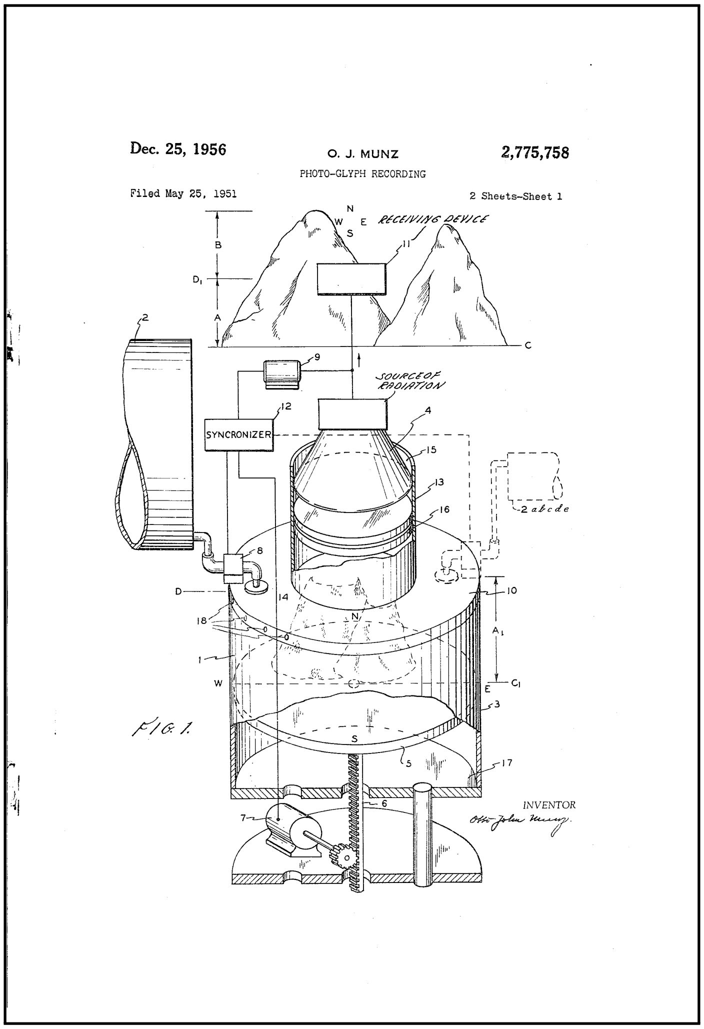

Figure 3.5: Figure from O.J. Munz's 1956 Patent, an Early Visualization of Stereo-lithography. Source: [50]

3.3.1 The Maker Movement and the Desktop Revolution

In the past decade, people often called "makers" have built, created, tinkered, and programmed very complicated and diverse technology projects, ranging from inventing simple open source programming to building a 3D printer from scratch out of items found around a typical garage. A lot of this creation has been fueled by the Internet and the rise of how-to videos and blogs. Now, more than ever in history, if someone wants to build or create something, they can. Most ideas can be created with simple and cheap parts procured off of the Internet and built using any combination of online videos.

To say that the maker movement is something new is a bit of a fallacy. As mentioned earlier in this chapter, humans have been making and tinkering for a long time. In the early 1900s, the magazine, *Popular Mechanics* brought new ideas and provided help on how to build new and interesting things right at home [52]. It could be said that the maker movement is merely one more step in free and creative thinkers building new and promising things. Today, people don't need large corporations to design a website and not even to build a 3D metal printer [53]. Independently, then, with one type of metal 3D printer, for example, one could hypothetically build any number of advanced parts, all in a garage and with limited financial resources. The maker movement brings about innovation and creative ideas, and it makes testing of those ideas easy. This is a new form of information dissemination that allows new ideas to be advanced rapidly.

The same movement has proven to be an important part in the recent interest and push behind AM. People can now afford personal rapid prototyping machines that cost in the hundreds of thousands of dollars in the 1990s. This is a similar cost trend that followed personal computers through the mid 20th century (Figure 3.6.) It seems possible that AM machines will take this path as well, with respect to performance and price and can be helped by the maker movement.

3.4 Three Dimensional Printing: Materials, Printing Techniques and Printers

3.4.1 Materials and Methods

Vat Photopolymerization

Photopolymerization is one of the oldest techniques 3D printing techniques. The process usually involves a liquid UV curable resin that, when exposed to a light or laser, hardens. This is the basis behind Chuck Hull's late 1980s patent mentioned earlier [11]. A vat of liquid material is either placed above or below a laser or UV light projector. A build plate is lowered into the liquid material either just below the surface or at the bottom of the vat, depending on where the light source or laser is located. The light or laser is then introduced to the liquid material and hardened layer by layer. This process has been shown to produce extremely fast builds [54]. See Figure 3.7.

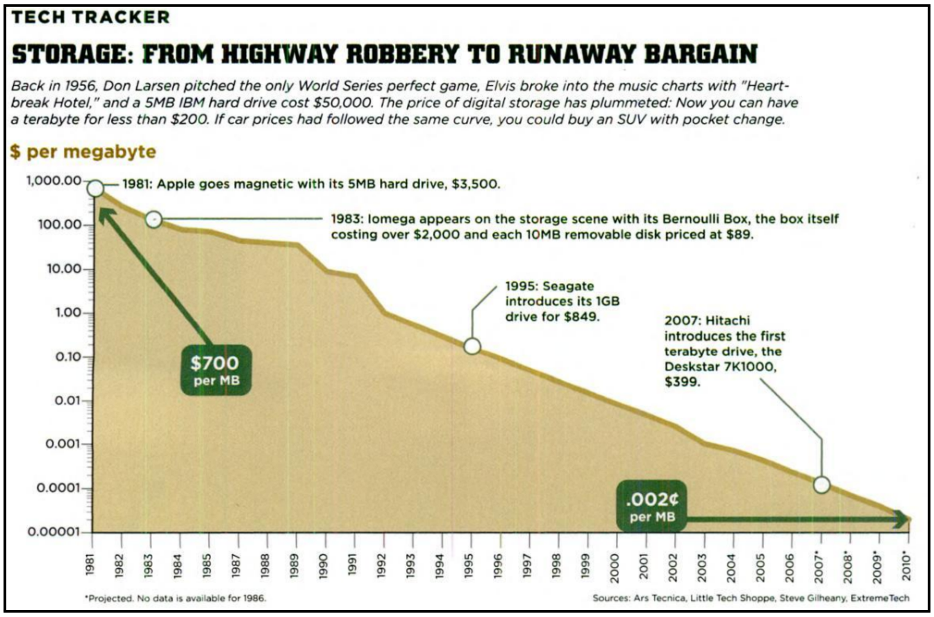

Figure 3.6: Computer Storage Cost Over Time Shows an Exponential Decrease in Cost Coupled with an Exponential Increase in Storage Capacity. Source: [50]

3.4.2 Powder Bed Fusion

The powder bed fusion (PBF) technique uses a level bed of material powder of either metal, plastic, or any number of other powdered material that is fuse-able, using a laser as the heating source. The initial layer of this powder is very thin. A laser (usually Co2) is then focused on the specific build area (e.g. x-y mm) that is to be solidified. Once that layer is finished, another layer of powder is placed on top and the process begins again. The layering process iterates many times until a three dimensional object is produced (see Figure 3.8). The PBF method allows for support material (un-fused powder), enabling more complex designs without the use of sacrificial supports.

3.4.3 Extrusion Based Systems

Extrusion systems have been the basis of the AM maker movement because of their low cost and ease of use. In general, extrusion systems take some type of melt-able/liquefy-able material, and form thin beads of that material into the outline of an object on the x-y plane. Outlining is repeated several times over with the extrusion head moving up on the z axis, with each thin layer, until an object is completed. Many materials are available for

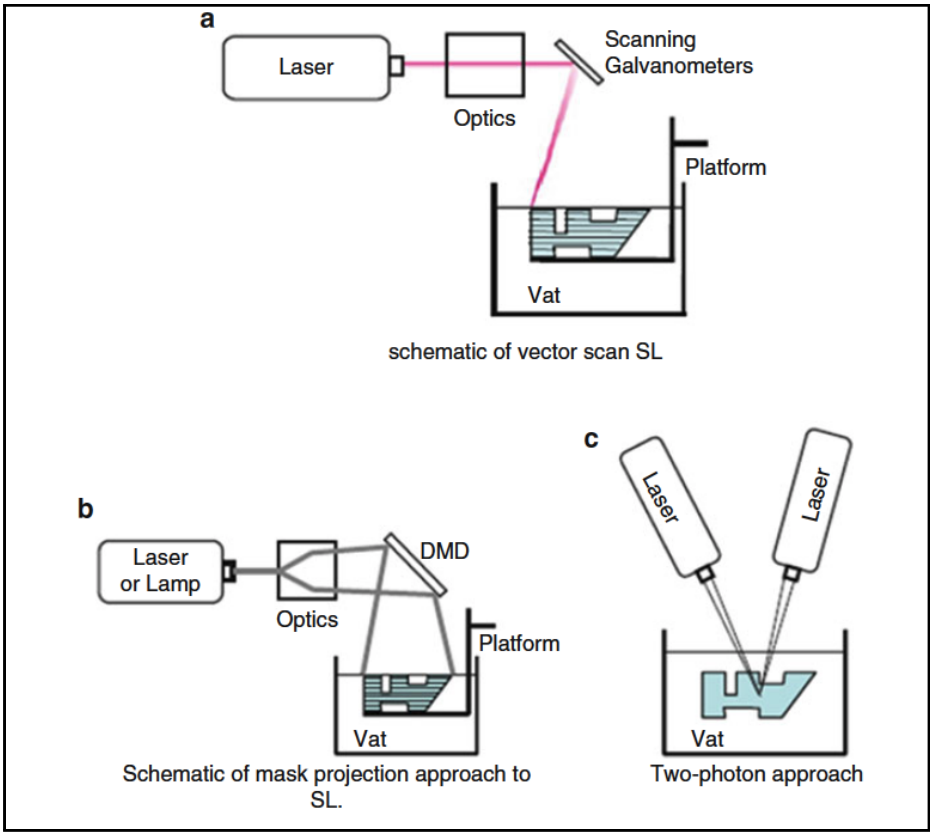

Figure 3.7: Vat Photopolymerization Processes. Source: [55]

extrusion based systems from plastic (ABS, PLA) to metal (titanium and aluminum wire) and concrete. (Figure 3.9)

3.4.4 Material Jetting

The material jetting (MJ) process is one that holds great promise but is still a developing AM technology. Shown in Figure 3.10, the MJ process follows the same basic principles of a traditional ink-jet paper printer. MJ also differs from PBF in that the materials are deposited from above via a jetting head. Material is deposited from small droplets of material on the x-y plane and then the jetting head moves up on the z plane to continue the full 3D print. With the MJ process, any number of materials can be combined into one object, enabling the printing of fully functional mechanical parts or electronic circuits [56].

Other AM processes include Binder Jetting, Sheet Lamination, Direct Energy Deposition

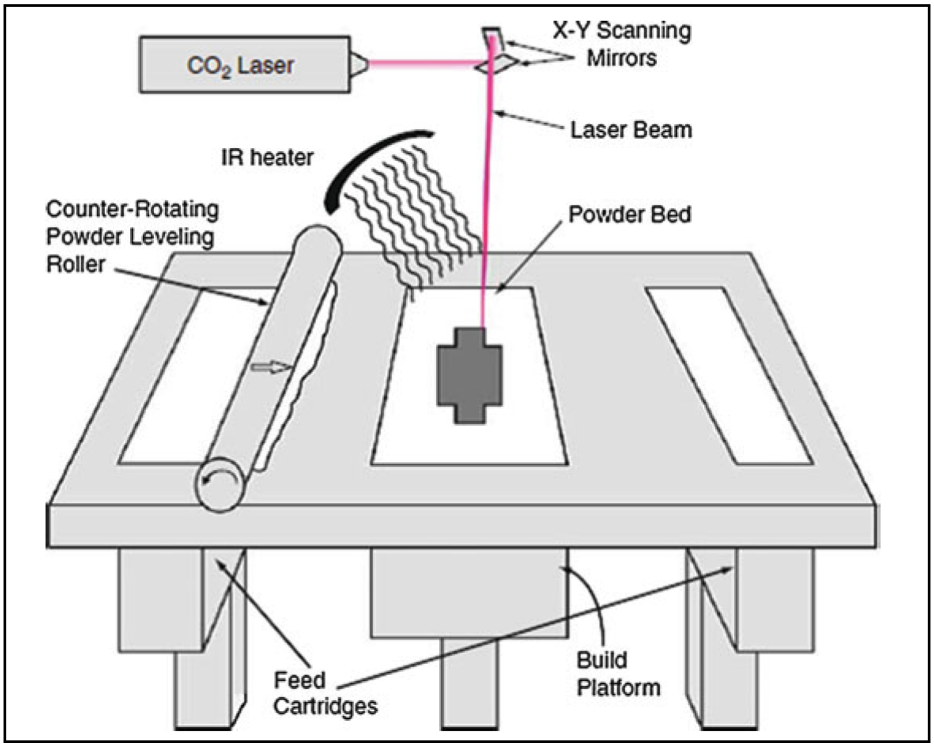

Figure 3.8: Powder Bed Fusion AM Process. Source: [55]

and Direct Write technologies; this thesis does not discuss these due to space constraints.

3.4.5 Future Materials and Methods

Companies have begun using multi-material printers to make stronger and more complicated parts. The company Mark Forged has printed a chain link out of carbon fiber [57]. This link was tested and failed at 11 tons [57]. Other uses for AM machines include not printing the final part, but rather simply printing the mold to then use traditional manufacturing such as injection molding or forging.

3.5 Data Formats for Three Dimensional Data Sets

With AM technology, what is printed is even more important than how it is printed. It is in the digital space that models are born and modified. It is also in the digital space that many of the issues and opportunities surrounding AM exist. Cyber security, the digital safeguarding of models and their geometry along with the process at which models are

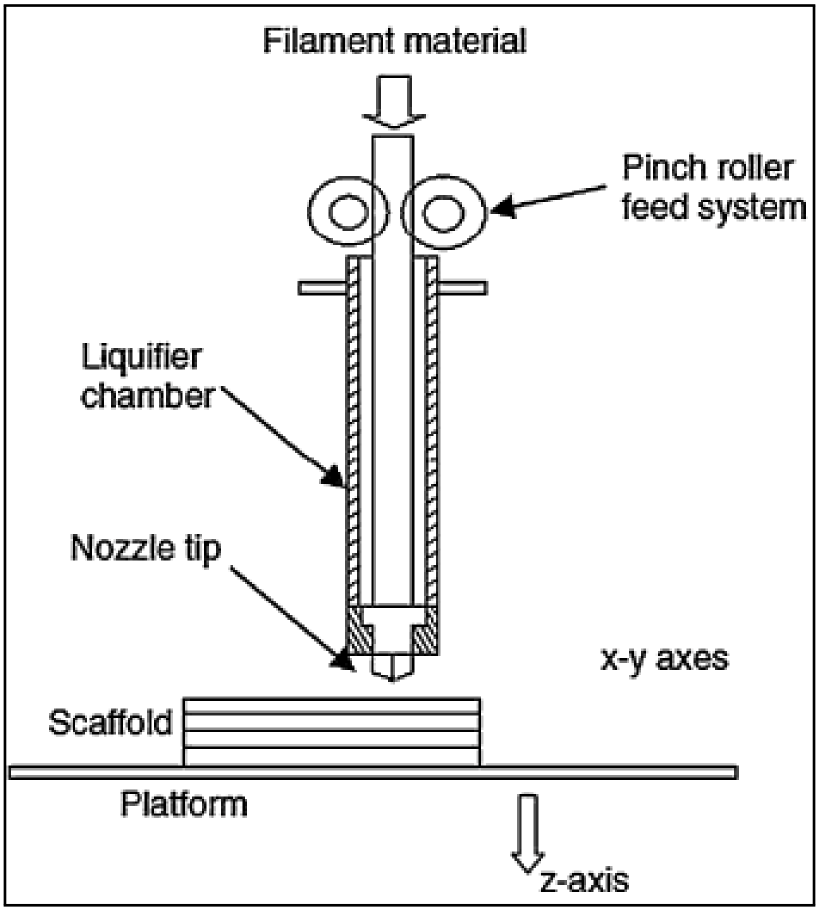

Figure 3.9: Extrusion Based AM Process. Source: [55]

planned, built, modified and distributed, is of great interest and importance to the USMC and USN. AM models may be used to produce parts of all varieties; on one extreme AM can make mundane pieces such as toothbrushes, while on the other extreme AM can make large buildings that people will depend on for shelter and protection. Section 3.5 discusses the opportunities and challenges surrounding 3D models in the AM domain.

3.5.1 History of Graphics Standards and 3D Data Formats

Early work in computer based 3D models generated simple yet powerful wire-frame models [58]. With a simple wire-frame depiction of an object in 3D space, a person looking at the image could basically fill in the blanks and visualize what the model was representing and how it was moving [58]. In the early 1990s, work began to place textures on the wire frames

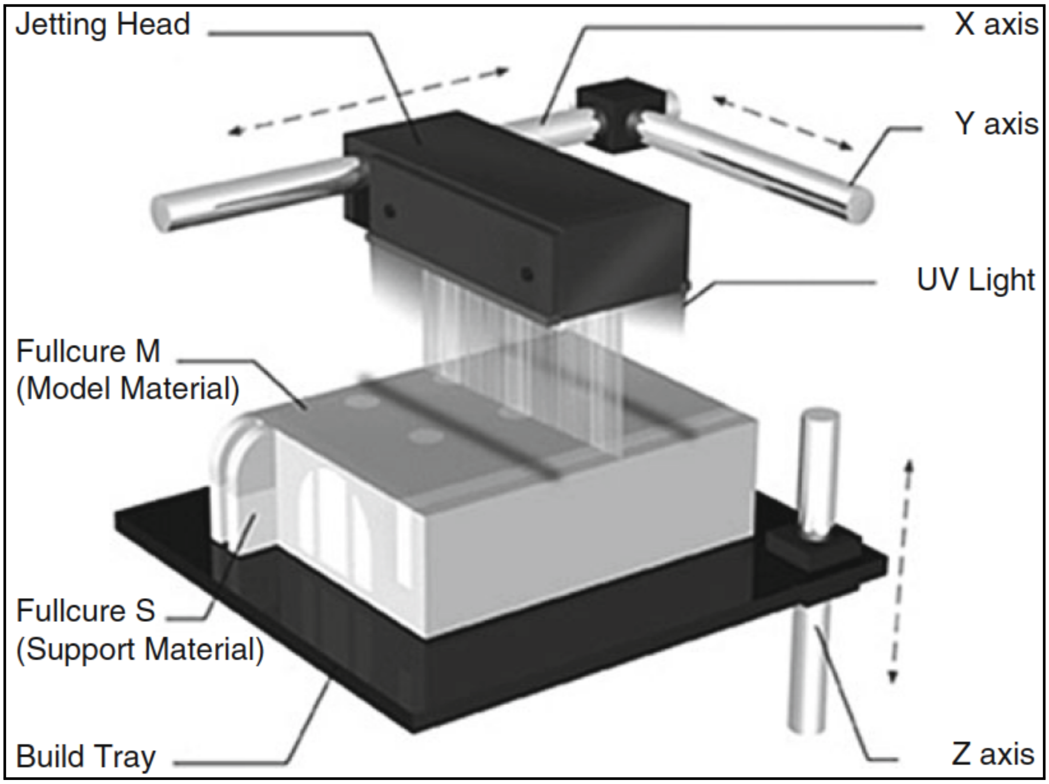

Figure 3.10: Material Jetting Process. Source: [55]

to better represent the model [59]. The texture work enabled a fully closed or watertight 3D object to be present in the digital space.

Early Graphics Standards

The first graphics standard was the result of a meeting of early computer graphics professionals in 1977. The result was the 3D Core Graphics System known as CORE [60]. As a standard, CORE enabled a common set of practices and a way to share data for computer graphic generation and use [60]. The 2D version of CORE had been a standard called Graphical Kernel System (GKS). GKS was used for CAD and eventually adapted for 3D. The next major standard that emerged was Programmer's Hierarchical Interactive Graphics System (PHIGS). PHIGS came about right as computers were increasing in speed to be able to render objects using "Gouraud and Phong lighting and shading models." [60] With the new ability to render objects, the simpler vector and wire-frame based computer graphics were becoming obsolete. OpenGL started to emerge as the de-facto standard until

the introduction of Virtual Reality Modeling Language (VRML). VRML was built to be an internet-based graphics standard where an internet browser would be able to render 3D graphics in a simple browser window. However, VRML was then superseded by the current computer graphics standard, Extensible 3D Graphics (X3D) [61].

3.5.2 Extensible 3D Graphics X3D International Standard

X3D is built on the VRML language, was adopted as an international standard in 2007, and uses XML language to enable integration with current World Wide Web technologies like VRML [61]. Using XML enables encryption and authentication which are open international standards that allow flexible substitution of cryptographic protocols and are accepted by industry in the U.S. and abroad [62]. The open nature of X3D has enabled much growth and non-proprietary development of a web-based modeling software. X3D is a royalty-free, open-standard file format with the potential to play a large role in the growth and spread of AM modeling techniques. As it currently exists, X3D enables network communication of 3D data across applications and provides an archiving format for 3D web models [61]. X3D's wide-use ability and low chance of obsolescence is of great interest to the USMC and Navy as both services look to move away from locked-in contracts and toward more open ways of doing business, while remaining fully secure.

Companies often use proprietary file formats to effectively lock in their customers into a certain software program. X3D provides a common basis for use that helps to avoid closed off and proprietary file formats, while, at the same time, ensuring the protection of intellectual property (IP) rights. The X3D CAD working group, of the Web3D Consortium, is tasked with developing and demonstrating the best practices for exporting CAD models into X3D to support web applications [62]. Current work by the X3D CAD working group includes "adding support for 3D Printing and 3D Scanning compatibly with the X3D CAD Component." [63]

Moving from one modeling language to another is an important and risky task when manufacturing parts and pieces that may be used on aircraft or on a truck that will be traversing hostile territory. The quality and dependability of that piece may be degraded when moving from one modeling software to another. X3D will allow for loss-less use of models and the security that will be needed when AM models and files need to be sent

electronically. [2]

Along with model security, establishing a work flow with XML Security (encryption and digital signature/authentication) is essential to USMC and USN AM operations. A common X3D model profile is possible for collective support of CAD, 3D printing, and 3D scanning, enabling efficient, secure and streamlined model handling [62]. The availability of X3D interchange provides multiple opportunities for archival preservation of digital models for faster reuse across the entire system life-cycle.

3.6 Building Information Modeling (BIM)

Building Information Modeling (BIM) theory has recently become a very important part of modern day construction and is an important element to look at with respect to how AM and CC models could be handled in the digital space. In the BIM process, a digital model is used not only for the design of the building but also used as a sort of gathering place for all that will either plan or interact with the building throughout its lifespan [64]. From initial design to final tear down of the structure, the digital model is used in architecture, engineering, and construction. Digital design has been used for quite some time, but, once the building is put onto 2D blueprints, the 3D digital model is no longer referenced for the remainder of the structure's life. Once the building information model is completed, the model / blueprint contains precise geometry and relevant data needed to support the design, procurement, fabrication, and construction activities required to realize the building [64]. The fiscal benefits and synergies of effort is readily apparent in the application of BIM. Those same efficiencies might easily carry over into the application and management of AM-specific processes and parts, and that is the goal of the Digital Twin process.

3.7 Digital Twin and Digital Thread

The process of using a Digital Twin starts after a part is designed in the digital space and is certified for its specific use. The digital model is then saved and placed into a repository where it will essentially mimic the real world part for testing and evaluation. Testing is traditionally performed using a prototype approach [65]. A prototype part is produced first

[2]Current NPS research is designing an open model repository server prototype which combines these technologies, using source code and design patterns demonstrated by the National Institutes of Health 3D print exchange.

and then destructively tested and verified for use. Once in use, a generalized statistical table is generated and employed based on the predicted life span of the part or piece; the same table helps to calculate the remaining life of the part until failure [65]. This is in contrast to the use of a Digital Twin where the digital twin constantly predicts and forecasts the system as a whole to better prepare other subsystems and support mechanisms in real time. See Figure 3.11. "The systems on board the Digital Twin are capable of mitigating damage or degradation by activating self-healing mechanisms or by recommending changes in mission profile to decrease loading thereby increasing both the life span and the probability of mission success." [65] The Digital Twin increases part lifespan through integrated and constant communication with its real world twin as to current stresses and hours used, allowing the Digital Twin to be analyzed and investigated without the need to remove the real world twin for examination, lessening down-time and increasing reliability. Digital Twin would be used not only from cradle to grave, but from conception to afterlife to rebirth.

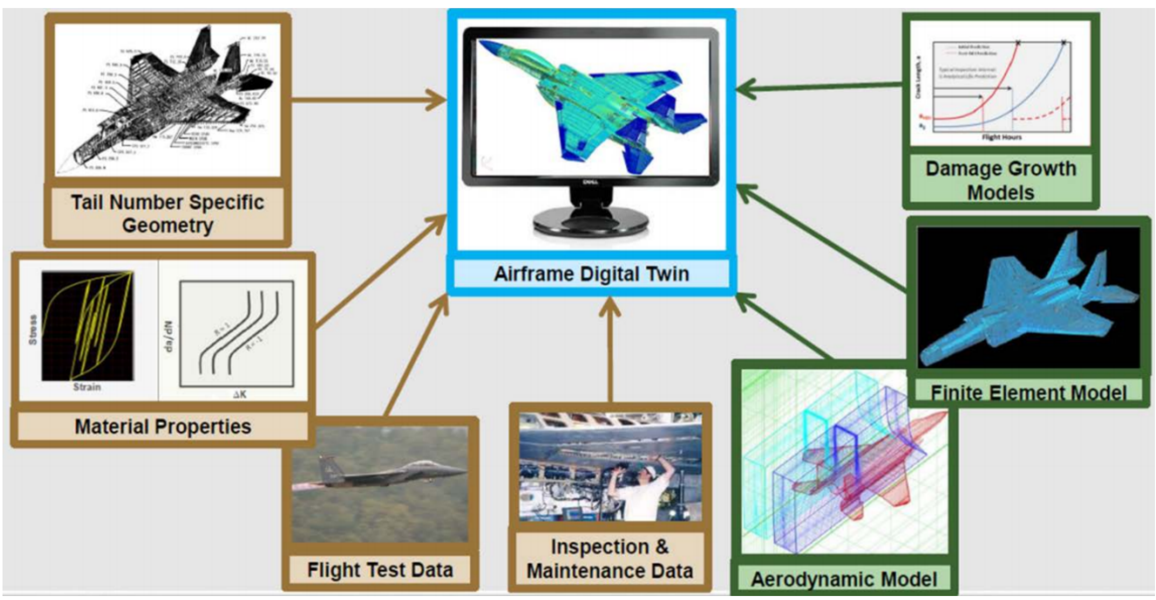

Figure 3.11: Digital Twin Process Shows How a Physical System Maintains a 3D Model of Itself to Mimic its Real-World Twin. Source: [66]

The digital thread for AM is focused on the actual design and manufacturing of the part and less on life-cycle management. "The term digital thread originated in the aerospace industry to describe an integrated systems engineering process for digitally managing the entire process from the 3D CAD design of system components through the manufacturing,

assembly, and delivery of the system." [66] The Digital Twin and digital thread concepts need to be integrated into the current DOD acquisition framework to best leverage their potential efficiency.

3.7.1 Cybersecurity and Digital Watermarking

Any discussion involving the digital space needs to include a discussion of security and operating in a hostile environment like the cyber world is known to be. In the 2014 Quadrennial Defense Review, Chuck Hagel describes the cyber environment, and says we need to be "prepared to battle increasingly sophisticated adversaries who could employ advanced warfighting capabilities while simultaneously attempting to deny U.S. forces the advantages they currently enjoy in space and cyberspace." [67] Given the nature of AM technology and the significance of its application domains, this reinforces that, what is printed is just and important as how its printed. If the USMC and USN adopt a policy of data-basing 3D models to eventually print those models, they will need to secure the actual 3D models and ensure their integrity.

Digital Watermarking and Intellectual Property of 3D Models

3D models in the digital space are made up of hundreds of thousands of polygons arranged in a way to emulate their intended shape [68]. Figure 3.12 shows an example of how polygons are used to emulate a computer based 3D model.

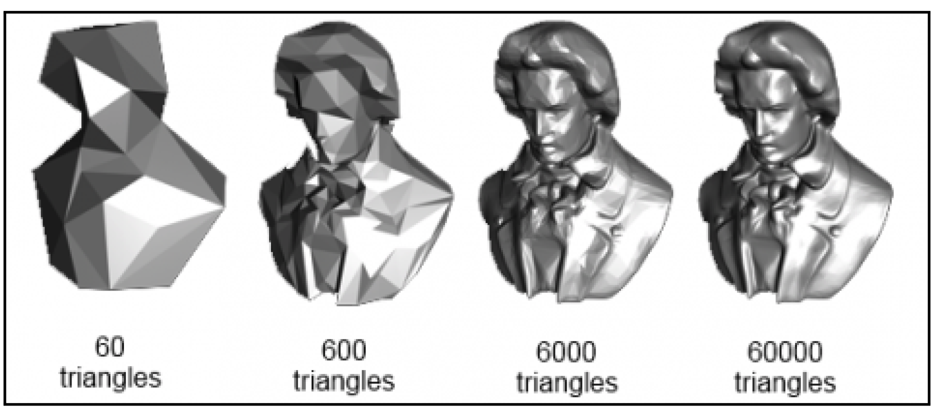

Figure 3.12: Low to High Polygon Count Show the Decreasing Return of Clarity When Adding More and More Polygons. Source: [69]

Harte and Bors discuss an algorithm-based method for producing a undetectable and unmodifiable watermark that can be placed onto digital 3D models to ensure the IP of that model as well as its intended fidelity is protected [70]. This method of digital watermarking involves the movement of vertices in the model, which could be a problem if the model is of a high tolerance aerospace part that will be subjected to high loads. Even moving or modifying just a few vertices could compromise the integrity of the final printed object. Another method involves slightly bending the polygons of a model, again imperceptibly, and then moving them back once the part is ready to be printed [71].

The idea of geometric digital watermarks for 3D printing is discussed in a paper by B. Marq et al. [72]. The theory is to make an imperceptible mark to a 3D printed object (such as imperceptible variations in coordinates, colors, et cetera) that can only be seen after scanning the object. They conclude that geometric watermarking is an important additional tool that can help to protect IP rights of models and also aid in quality assurance (QA) of the printed model [72].

3.8 Summary

This chapter provides details of the AM world as a whole. From current physical technologies to digital technologies, AM is a burgeoning field that holds great promise. The USMC and USMC need to thoroughly consider several aspects when looking into what AM technology is and what is in the realm of the possible. Despite many challenges, many opportunities also exist. If the USMC and USN are to succeed in this domain, a well thought out and thorough strategy should be developed and strategically adapted as AM technology enters the mainstream.

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CHAPTER 4:
Diffusion of Innovation

AM is not a new technology. However, AM still has yet to be adopted by the vast majority of intended, let alone possible, users. As demonstrated in Chapter 2 and elaborated on in Chapter 3 through reviewing AM methods, AM's diffusion within the military and within the commercial sector has been slow and deliberate. Chapter 4 presents a more focused analysis of diffusion of innovation and the AM domain and characteristics to examine why AM has been so slow to diffuse and how that deliberate, methodological diffusion can benefit the USN and USMC.

4.1 Introduction

Communication is the lynchpin of diffusion of innovation theory. Everett Rogers, the father of modern day diffusion theory, defines diffusion as "the process by which an innovation is communicated through certain channels over time among the members of a social system. It is a special type of communication, in that the messages are concerned with new ideas." [32]. For example, one individual communicates their message regarding a new idea or new technology to a second individual. Based on the ability of the first individual to persuade the second, the second will choose either to adopt or not to adopt the new idea. In its most distilled form, diffusion of innovation gives no further information to the second individual so that only the idea itself and the first individual's presentation stand as the basis of the second individual's decision making process. In modern society, however, such diffusion in isolation rarely happens. People are bombarded with information at every second of every day through smart phones, the internet, social media, television, radio, and printed press. When a person's only source of information came from word of mouth or by reading a newspaper, diffusion of innovation was vastly different. The second individual had only themselves, their own experience, and the information from the first individual; essentially, they had only the new idea itself to ponder. That was it. Today, it's a wonder if a friend or colleague can even get through to another with a new idea let alone persuade them to accept it. Although the information on user acceptance of AM and CC is limited, many studies have previously been done on similarly disruptive technologies. [5], [32], [73]

4.2 Basic Concepts of Diffusion of Innovations

In 1989, through a study on email, Fred Davis proved that the "fundamental determinants of user acceptance were perceived usefulness and perceived ease of use" so that how easy it was to use and how useful it might be were directly correlated with whether and how quickly that technology would be adopted. [33] In his study, Davis found that a perceived usefulness and ease of use of new technologies were directly correlated with the adoption of that technology (his case study was on e-mail). Take the Dvorak keyboard for example. The modern day QWERTY keyboard is based on typewriters of the late 1800s [32]. The keys were laid out to slow down the typist, so mechanical jams would occur less frequently. Using the Dvorak keyboard, 70% of the typing is done on the main home row, where the fingers rest, compared to only 30% of the typing done with the traditional QWERTY keyboard [32]. With the potential efficiency in using the Dvorak keyboard, why has it not become the de-facto typing method? The Dvorak keyboard failed to fulfill the two elements of Fred Davis's theory. The Dvorak keyboard's perceived usefulness and ease of use were not great enough to make people give up the established QWERTY keyboard. The communication channels of the diffusion were either nonexistent, or people simply were not amiable to a new typing idea.

4.3 Rate of Adoption and the S-Curve

The rate of adoption for any innovative technology is naturally based in time. The variable represents the period of time it takes for a percentage of the majority of the population to adopt a new technology, usually depicted in a s-curve as in Figure 4.1; the rate of adoption of some innovation can have many possible outcomes. [32] For example, the telephone had a rate of adoption that spanned decades compared to the rate of adoption of smart phones, already so predominate and that may reach saturation in less than ten years [73]. The study of diffusion of innovation seeks to determine how and why adopters choose to accept one technology quickly and in large numbers while, in some instances, they choose not to adopt at all. In some instances, rates of adoption reached a plateau at some percentage of adoption and failed to gain any new adopters [32]. Rogers describes the diffusion of an innovation as more of an uncertainty-reduction process [32].

The rate of adoption studied by Rogers parallels Fred Davis's efforts and study [32], [33] which shows perceived usefulness as an important indicator of adoption rates. If a technol-

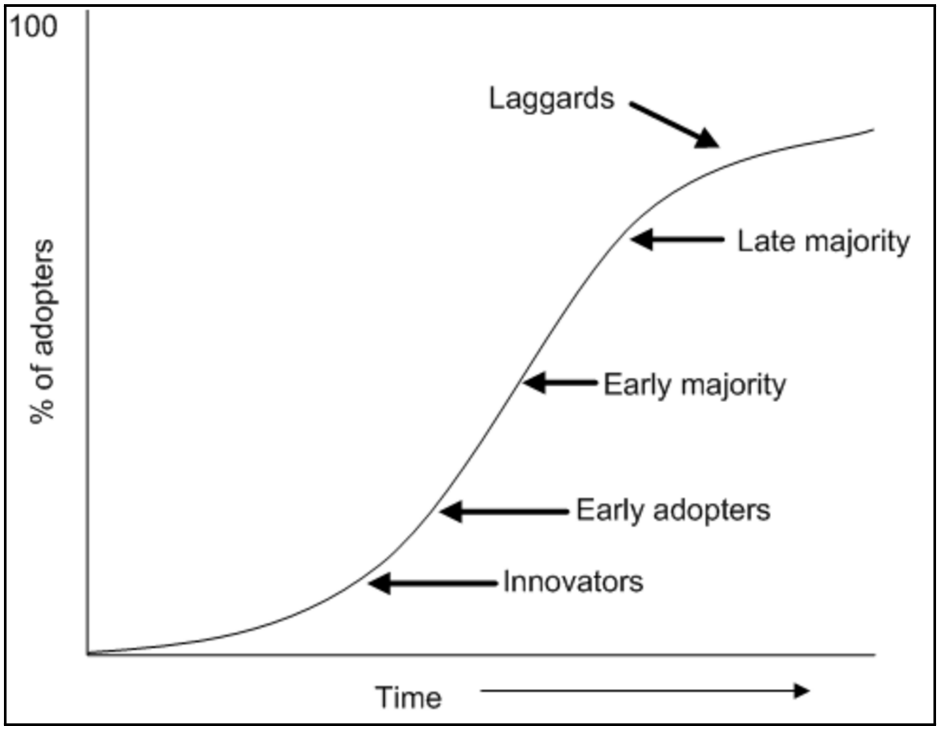

Figure 4.1: Everette Rogers Rate of Adoption Curve Showing the Percent of Adopters Over Time. Adapted From: [32]

ogy is not viewed as useful, why would anyone want to take the time to learn or adopt it? It is difficult, though, to gauge a usefulness of a new technology without some investigation into its usefulness and ease of use. Most initial investigation is done by the innovator group and then progresses to the early adopters. At any point in time when the innovation is found to not be useful, adoption will slow or even decrease as the innovation is deemed not as useful (shown in Figure 4.2).

4.4 Communication Channels

Rogers describes the communication channels, as they relate to innovation, as based around social and local circles of people and less around scientific results and studies [32]. A person will be more likely to adopt a new and emerging technology if their friend endorses it. If someone in a position of trust and respect says that a new technology will do what it says it will, the person receiving that information will be more likely to adopt it [32]. As the human race enters the information age, these social circles used to receive endorsements

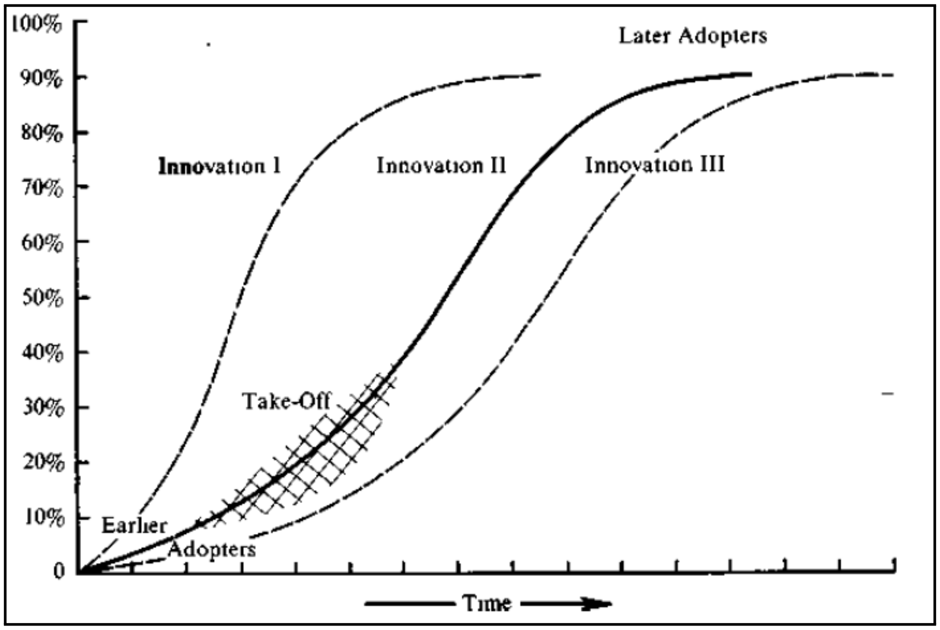

Figure 4.2: Innovation I, II, and III and Their Differing Percentage Rates of Adoption Over Time. Source: [32]

continue to widen and grow increasingly complex.

Take Facebook, for example. According to a survey conducted by the Pew Research Center in 2014, the average Facebook user had 200 friends [74]. People in the age range of 18-29 had an average of 300 friends. The average Facebook user "liked their friends' content and commented on photos relatively frequently, but most did not change their own status that often." [74] The survey suggests that people received more information via Facebook and social networks than they produced [74]. Social media made the acts of endorsing novel solutions by someone's friends extremely easy, thus demonstrated ease of use and possibly also usefulness.

4.5 Communication Channels

Diversity among someone's Facebook friends is likely. According to Rogers, those friends would fall into one of five different adopter groups: innovators, early adopters, early majority, late majority, and laggards [32]. Rogers suggests that innovators generally have a higher degree of information exposure and will process more information than other adopters. With this greater information, the innovator is able to lower their uncertainty about a certain

technology; Rogers points out that media thus has a greater impact for innovators than for people who follow them in the adoption process [32]. Although innovators make up a small percentage of the adopter population, they serve an important and critical role [32]. The following four adopter categories rely more on interpersonal communication than the innovators: early adopters, early majority, late majority and laggards [32]. Early adopters follow the innovators - they still gain some of their information from media, but they progressively receive more information from their localized surroundings and interpersonal communication channels [32]. The early majority adopters gain more information from their social circle and less from external mass media. The remaining two groups of adopters, the late majority and the laggards, receive more information from their social circle than any other adoption groups [32].

4.6 Role of Leadership in the Adoption Process

According to Rogers, the early adopter category has the greatest number of opinion leaders [32]. The opinion leaders have greater access to information and are able to effect change in their followers [32]. A top down support for adoption of an innovation in an organization is an important aspect for the successful incorporation of that innovation into the organization [75]. To successfully adopt a new and emerging technology, USMC and USN leaders must vocally and repeatedly sound their support. Without that support, a technology often struggles to be incorporated, especially if there is no sense of clear usefulness and ease of use [33].

Any military organization differs from a corporate organization. The USMC and USN have specific requirements that may or may not parallel the industrial domain. Given the complexity and importance of the mission of both services, it is more imperative than ever that Marines and Sailors adopt certain technologies. In the 14th and 15th centuries, the largest killer of sailors was scurvy [76]; back in 1601, it was discovered that ingesting three teaspoons of lemon juice everyday prevented people from developing scurvy [76]. Even though this breakthrough was proven, scurvy was still prevalent. It was not until 1865, almost 270 years later, that the British Board of Trade made use of lemon juice mandatory [32]. With such a game changing technology proven, why was lemon juice not used faster? Rogers hypothesizes that, perhaps, the leaders who discovered the advancement did not hold high enough office to be influential [32]. Rogers goes on to say that technologies

with much higher profiles, such as ships and cannons, possibly received the majority of the attention and budget, relegating the simple and cheap fix for scurvy to the bottom of the proverbial pile [32]. Considering that scurvy likely made a substantial difference to maritime operations, the USMC and USN should take this example to heart, ensuring that the current government acquisition system does not get unduly influenced and led by contractors, lobbyists, and uniformed technology champions rather than fundamental needs.

Of course, the uniformed technology champions serve an important role in the adoption of critical technologies. They serve as the opinion leaders and are able to effect the change needed for the adoption of a technology. In the same vein, the champions can push the wrong technology, resulting in the adoption of expensive and under-performing technology such as the USMC expeditionary fighting vehicle. This expeditionary fighting vehicle, though canceled in 2011, nevertheless consumed a total of $3.7 billion over seven years, 2003-2011 [77]. That development happened around the same time as social-network centered warfare began to come to light. Arthur Cebrowski and John Garstka laid out this potential gap in DOD efforts in 1998 [78]. They, possibly by mistake, predicted the social-network warfare model that has become so prevalent in recent years [78]. Their revolutionary theory that new and non-wired networks would be the new enemy was almost immediately relevant with the 2003 invasion of Iraq. The enemy used disposable emails and traded bomb making techniques through anonymous internet access [78]. A 2007 Wired article states that, "the fact is, today[,] we rely on our troops to perform all sort of missions that are only loosely connected with traditional combat but are vital to maintaining world security. And it's all happening while the military is becoming less and less likely to exercise its traditional duties of fighting an old-fashioned war" [79]. Had the DOD invested $3.7 billion into studies and efforts surrounding networked warfare, one could hypothesize that perhaps the insurgency in Iraq, and more recently the rise of the Islamic State, would have been thwarted. The adoption of technology in the government services is typically understood as a generally slow process, while industry acquisition can be fast. Leaders endorsement and funding of new technological innovations are essential for most efficient acquisition of new technologies in any organization, including military domain.

4.7 Diffusion Models

In 1985, Fred Davis proposed the much referenced Technology Acceptance Model (TAM). This model provides a system prototype where a user could, in turn, use the system and gauge their motivation to actually purchase and implement the system into their everyday life. [80] In his study, Davis looked at how to help system designers and provide them with better conditions for building and introducing new technologies to groups of adopters. [80]

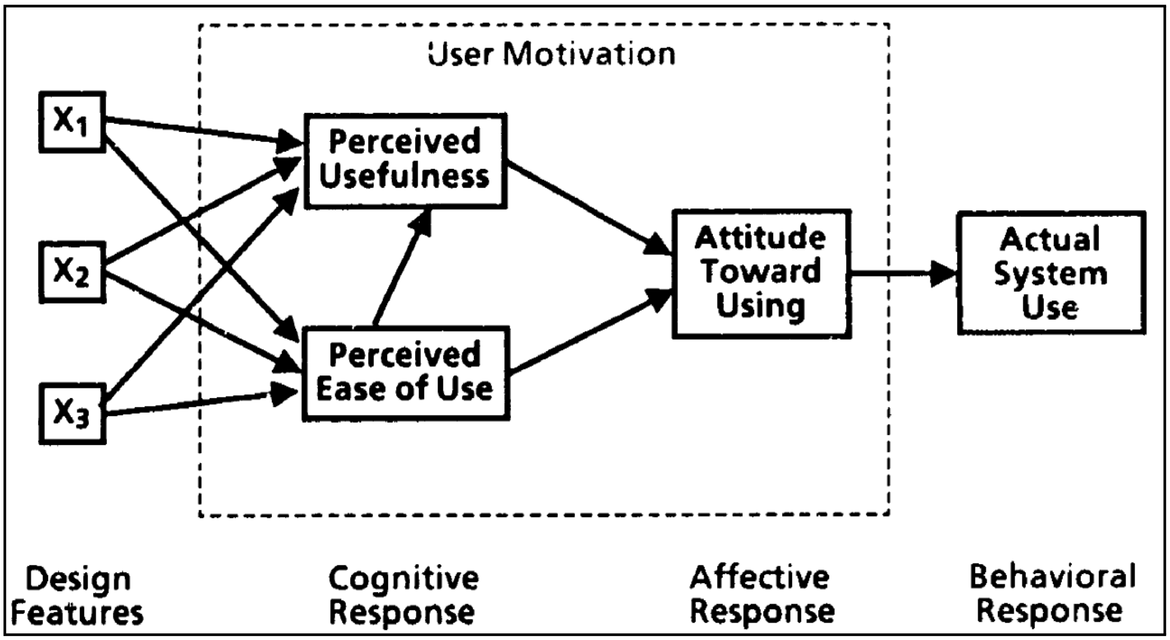

Figure 4.3: Technology Acceptance Model. Source: [80]

In Figure 4.3, individual users are represented by X; their motivation for adoption is rooted in perceive usefulness, perceived ease of use, and attitude toward using. The similarities carry over into Davis's 1989 study of user acceptance of e-mail [33]. His work suggests that a person is going to use a new technology only if their perceived benefit from using it, coupled with the ease of actually using it, is greater than the cost to buy and learn the new technology [33].

As mentioned earlier in Section 4, Everett Rogers created the initial diffusion of innovation model. Figure 4.4 illustrates the elements of Rogers model. It shows diffusion process where the agents receive information and what they do with it; they either reject the innovation or accept it and tell others about it [32].

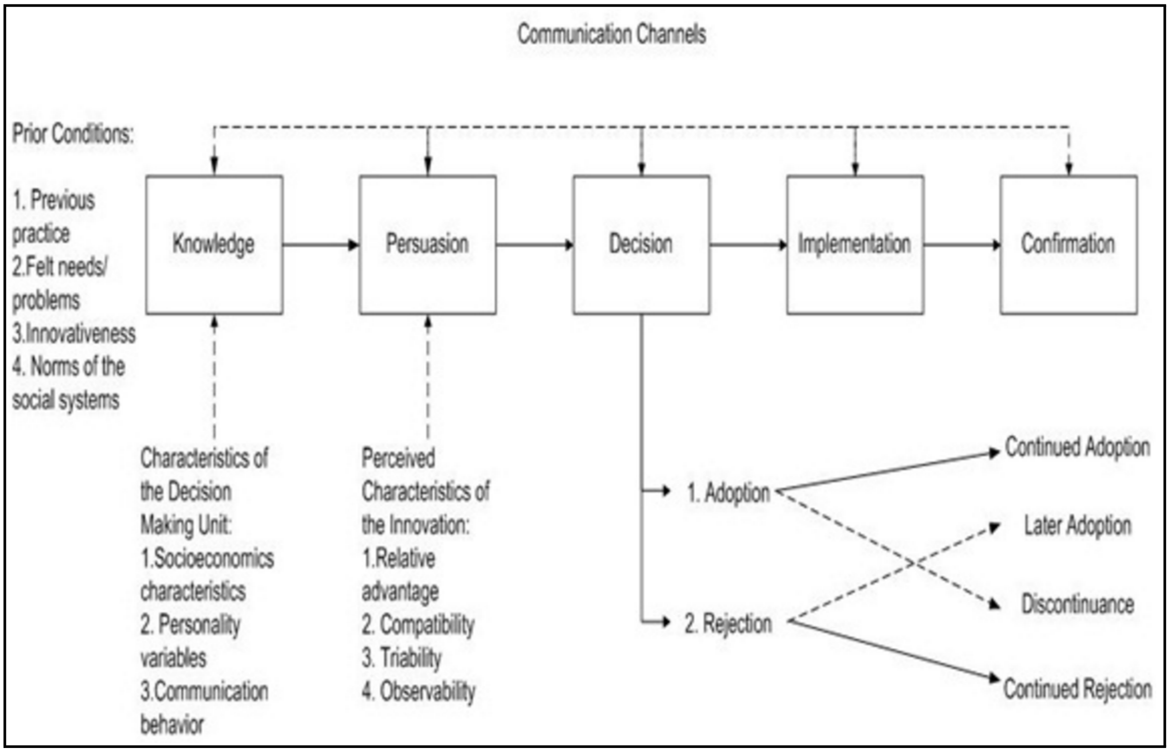

Figure 4.4: Rogers Innovation Diffusion Theory. Source: [32]

In 1986, J.D. Eveland wrote about technology as information and how that information percolates through society. Eveland said that information exists for the sole purpose of people using it in their everyday life and to their benefit [81]. His main theory revolves around action-centered diffusion, where an idea or innovation is molded and modified progressively through five stages: agenda-setting, matching, redefining, structuring, and interconnecting [81]. In agenda setting, two ideas that were once not connected are brought together then matched; after matching, the combined idea is refined, redefined, then structured into an accepted idea, which is then interconnected with current ideas and technologies [81]. Eveland's approach contrasts other diffusion models that are focused on individuals accepting and using innovations.

Wolfgang Keller discusses a theory of international technology diffusion in his work *International Technology Diffusion* for the National Bureau of Economic Research [82]. Keller formulates a series of regressions that help conclude that the rate at which a country adopts technology from other countries is directly related to its trade with other countries [82].

Countries that have open trade polices will have a greater rate of technological diffusion.

The Fichman model is a diffusion model that helps determine the correct amount of innovation use among a corporation [83]. Fichman's model suggests that a corporation needs to have a correct blend of innovation - not too much but not too little either [83]. According to Fichman, if a corporation chooses not to adopt technology at any level, it will fail; similarly, if a corporation adopts too many technologies, it's also likely to fail [83]. Fichman indicates that the correct blend of innovation maximizes its usefulness. The idea of balance is an important aspect of innovation theory as it discusses the over-adoption of technology and how that could negatively affect the organization. With too little or too much both having negative impacts, the USMC and USN also need the right balance in adopting technologies. AM's deliberate innovation, once pervasively adopted, can help both services succeed in accomplishing their missions.

4.8 Summary

Chapter 4 provided an overview of the diffusion of innovation theory, explored different examples of innovation diffusion, and discussed several diffusion models that have previously been proposed. Chapter 5 takes the foundational AM information already described and applies those details to demonstrate how CC can benefit the USMC and USN.

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CHAPTER 5:
Contour Crafting in USMC and USN Operations

5.1 Introduction

With the dawn of AM only now rising, a tremendous amount of interest regarding the use of AM technologies centers on the construction of structures and buildings. A simple way to think about constructing building with CC is by conceptualizing the way traditional brick buildings are constructed. Walls are made by placing brick and mortar along a vector, then, once the desired length is achieved, by placing more brick and mortar in another layer on top of the first. Layers are repeated until a full wall or structure is built (see Figure 5.1). CC is very similar, yet more fluid and automated. In CC, an extruder, as described in Chapter 3, feeds out a mortar concrete paste in layers with one resting on top of the other, repeating until the desired wall is fully constructed (see Figure 5.2).

Figure 5.1: Traditional Brick Laying Technique. Source: [84]

To be at the forefront of the CC revolution implement CC's full advantages, the Navy and Marine Corps must study what aspects of their missions can be best assisted by and can benefit most with the introduction of CC. If the Navy and Marine Corps had the ability to print concrete structures, on demand, would this benefit them and in what ways? Two

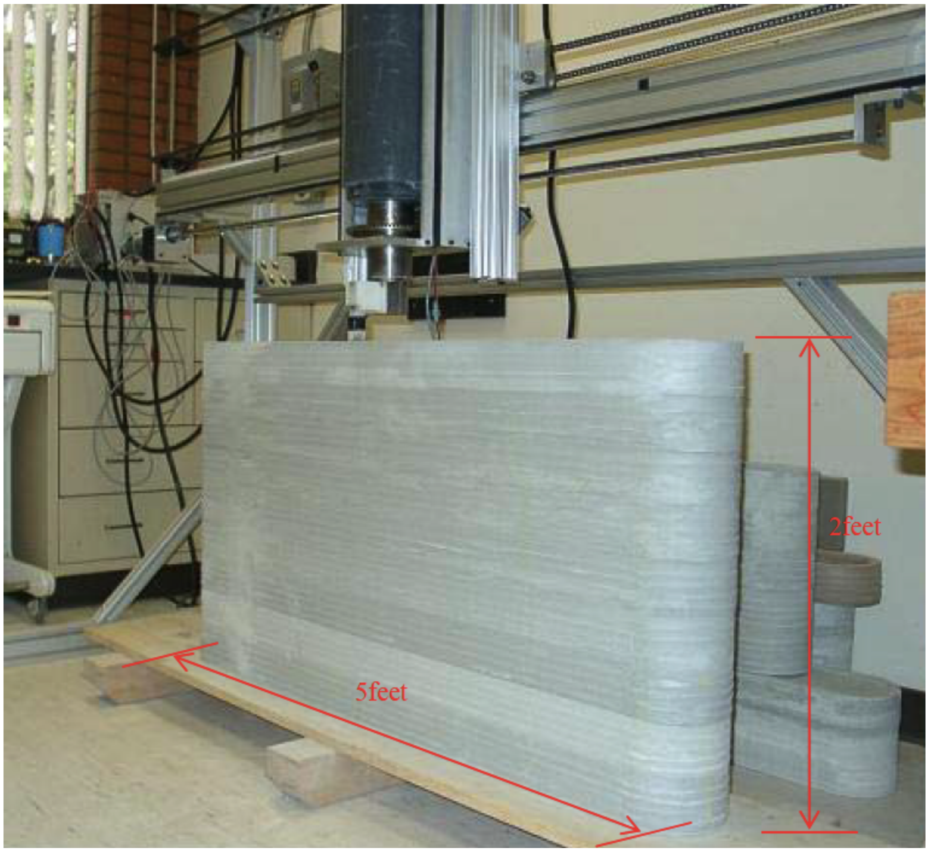

Figure 5.2: Contour Crafting Technique Building Concrete Walls. Source: [85]

specific Navy and Marine Corps teams who would benefit immensely and immediately from the introduction of Large Size AM into their mission are the Navy Seabees and the Marine Corps engineers. Chapter 5 examines the potential and projected benefits and considerations for the adoption of CC by the USMC and USN.

5.2 Contour Crafting, 3D Printing with Concrete

Dr. Behrokh Khoshnevis of the University of California continues to be the leading pioneer in the field of AM of structures [22]. According to Dr. Khoshnevis, after the 1994 Los Angeles earthquakes, he was patching cracks in the concrete walls of his home and had an epiphany. [86] Why not use a simple trowel to help extrude concrete for the building of walls and buildings? [86] If used correctly, this trowel could build a home automatically [86]. Over the past two decades since, Khoshnevis designed and patented his novel approach, and

he is now ready to deploy a large size 3D concrete printer that actually has the capability to 3D print a 2500 square foot house in 24 hours [22]. Current builds made of concrete structures that use both block and foam forms take no less than four days and require a platoon size element for construction. Plus, a CC machine requires only two people, one to set up the machine and one to supervise the print, with possibly two assistants [87]. In contrast, a comparable concrete structure made using a traditional approach requires at least 15 to 20 people and far more than four days, let alone 24 hours. However, the low cost of human labor using CC does not mean there's no cost. The printer and materials, of course, carry their own cost. However, one CC machine, once built, can potentially be used to produce many structures. Dr. Khoshnevis's technology, termed Contour Crafting, uses a large gantry system and specialized extruder and feed system to print a concrete building layer by layer (Figure 5.2.) Open spans, such as doors and windows, are bridged with a beam and printing of new (higher) layers is continued on top of the beam [22]. Future advancements in this technology promise to bring the autonomous incorporation of plumbing and electrical connections in line with the larger print [22]. Contour Crafting is not something that will be ready in the future; rather, Contour Crafting is ready now. It could be argued that this technology is not only disruptive, is it revolutionary in terms of projected benefits for many domains that need rapid building of shelters and structures.

5.3 Humanitarian Aid and Disaster Relief Missions

Looking specifically at the impacts Contour Crafting would have on a Humanitarian Aid and Disaster Relief Missions (HA/DR) mission, one can easily see the benefits that CC technology could bring to many application domains.

The Haiti earthquake was the fourth worst natural disaster in terms of lives lost in the 20th century; 310,000 people died. [88] After the earthquake, approximately two million more people, one fifth of Haiti's population, were homeless. [89] In response, the Navy and Marine Corps teams were organized under the Joint Task Force Haiti (JTF-Haiti), and, as a joint team, they took active part in Operation Unified Response. [88] Falling under JTF-Haiti, the Joint Force Maritime Component Command (JFMCC) was comprised of two Amphibious Ready Groups (ARGs), the Bataan Amphibious Ready Group and the USS Nassau Amphibious Ready Group. [88] Phase II of JTF-Haiti is where AM structures would have proved most invaluable. During phase II food, water and shelter were provided

to those who need it most urgently [88]. Non government organizations were fast to distribute tents indiscriminately to anyone who wanted one [89]. Large tent cities, later on, became epicenters for crime and unsanitary conditions; some thought that the tent cities did more harm than good. [89], [90] The same study suggested that, even five years after the earthquake, approximately 100,000 people still lived in these unsanitary and unsafe tent cities [90]. It is suggested that, had a CC machine been available, permanent concrete housing for two million people could have been provided in 40 days with 2,000 CC printers. [3]

Providing the shelter for those who might not otherwise have it fills a crucial basic human need. Not immediately evident is the additional economic benefit of ensuring safe and sanitary shelter. A 2005 USAID report details the economic implications of providing shelter after a natural disaster; the USAID study conducted surveys and interviews over three years in Sri Lanka, El Salvador, and Colombia [92]. The report summarizes that, “in all three cases, there is an increase in household welfare over time. In El Salvador, data shows a welfare multiplier of 6.2 or higher (investment of $1 million in the provision of emergency shelter results in increased income flows that are equivalent to household income increase of $6.2 million). In Colombia, a multiplier of 10 or more, and, in Sri Lanka (with a significantly shorter time frame, less than one year), a multiplier of 1.6 – 3.2 [percent].” [92] It is, therefore, safe to project that any investment in the provision of shelter to a post-disaster area would yield a large multiplier in household welfare. The Navy and Marine Corps team would not only be providing shelter via CC, they would be providing prosperity to an affected region. It could be said that, in effect, they would be "printing prosperity." The effort directed towards securing order and peace after a natural or man-made disaster has a great chance of making a region (or country) stronger and also, by citizens having more faith in their government, the festering and growth of insurgencies more difficult and less likely. Therefore, by ensuring the third leg of what humans require to survive (food, water and shelter), USMC and USN Contour Crafting would therefore contribute toward preventing wars before they even begin. The Navy and Marine Corps would not even need to wait for natural disasters to strike to provide housing for lower

[3] One printer can print 2500 square feet in 20-24hrs. Per USAID one person requires 100 square feet of shelter per day [91]. So for 2,000,000 people, (2,000,000*100) square feet of shelter would be required. 2,000 machines could print this amount of shelter square feet in 40 days. This, of course leaves out planning for the structures and the engineering that would also need to take place.

income countries. The benefits of sufficient shelter come with or without a natural disaster. Millions of dollars per year are already spent by the DOD and Department of State in the construction of housing, schools, and other structures. The money could be stretched further using CC. A team could be formed to determine the best places to provide needed shelter to coordinate with the host government, and to provide that critical third leg of survival to help bring about economic gains to any country in urgent need.

5.4 Other Applications of CC

Providing shelter is one aspect of a CC technology. Another comes in equipping Sailors and Marines with machines capable of 3D printing, so the barracks-huts (b-huts) would no longer have to be made of plywood reinforced with sandbags. Concrete structures could be erected, providing piece of mind to those residing in b-huts. Additionally, the construction of those structures would be done with minimal manpower. The saved manpower could be redistributed to perform other critical tasks. Runway repair and pier construction would be executed autonomously and with considerable speed. Command and control facilities could also be printed with all electronics embedded. The possibilities are so broad that a comprehensive strategy needs to be developed for all services in DOD.

5.5 Military Use of Concrete: A Not-So-New Idea

A little know piece of history is the use of concrete ships in WWII that resulted from the shortage of conventional steel. While concrete is still used for the construction of barges, one would not immediately think that concrete would be a good candidate for something that needs to float. This principle has been tested every year in the ASCE (American Society of Civil Engineers) National Concrete Canoe Competition (NCCC) held in and around the U.S. [93] This reinforces Archimedes's principle which says that a boat only needs to displace a weight of water equal to the weight of the boat [94]. Using Archimedes's principle and CC technology, Sailors and Marines could print floating barges, link them together, and build bridges in a matter of days. Future designs of CC machines include setups capable of printing pylons for bridges underwater and power windmills with a structure-climbing printer.

5.6 Risks and Barriers to Adoption of Contour crafting

The risks and barriers associated with CC technology mostly lie in the supply of concrete and the structural capability of the finished product. To make concrete, one needs three types of materials: cement, aggregate, and water. All three can be brought on missions, or, even better, sourced when and where needed. Past studies examined the use of local materials to make concrete in situ. [95], [96] Other studies examined the use of materials other than concrete such as mud and sand. [97], [98] NASA is even studying the use of CC for use on the Moon and Mars with local soils available on those celestial bodies. [99] Additional lines of research would need to be conducted to examine the suitability of the printed concrete and its strength. The U.S. Army Corps of Engineers is currently studying these types of issues with their Automated Construction of Expeditionary Structures (ACES) Project. [99]

With respect to CC, and in response to the survey conducted for this thesis and detailed in Chapter 7, leaders suggested that they can definitely use a capability to expeditiously manufacture the concrete culverts destroyed by improvised explosive devices (IEDs). It was stated that IEDs were generally placed under roads in concrete or metal drainage culverts. Once exploded, the culverts would need to be replaced to allow for proper drainage, but replacement culverts were very difficult to obtain. Blast walls were another suggestion as these were very costly to ship and replace when destroyed. An image of a 3D printed blast wall was shown earlier in Figure 5.2. An example of a traditional blast wall is shown in Figure 5.3. Another idea for the use of a CC machine suggested by interviewed leaders, was to print command and control buildings with electronics embedded in the walls. These ideas are in addition to the established use of a CC machine to construct shelters.

5.7 Integration in Current Force Structure

Given the nature of the tasks and various skill sets of different units of the U.S. Navy and U.S. Marine Corps, it is highly likely that CC printers would provide the most benefit when attached to Navy Seabee units, the Navy and Marine Air Ground Task Force's (MAGTF) first call when the construction of structures is needed. After the testing and evaluation of strength is completed, and viability of Massive AM deployment is proven, the Seabees along with Navy Facilities Command (NAVFAC) would need to establish a concept of operations (CONOPS) on how to best incorporate CC into current projects and plans. Smaller CC printers could be used by the USMC for expeditious base operations to include fortifications

Figure 5.3: An Example of a Traditional 8 Foot Tall Cast Concrete Blast Wall in Baghdad, Iraq. Source: [100]

such as machine gun nests or quick runway repair. These machines could work in the open rather than under cover, so that enemy locations would be revealed if the concrete printer were fired upon, another benefit that risks no life. As with any revolutionary technology, a firm requirement does not currently exist. Similar to some other novel technologies, large masses of users may not immediately see clear and large benefits from CC's deployment and adoption. The USMC and Navy do have continuing, unwritten requirements to become faster, lethal and cheaper, and any innovative technology that supports those characteristics, including CC, should be carefully examined and leveraged. [4]

Additive Manufacturing (AM) can have a profound effect on multiple Navy and Marine Corps logistical processes. The following scenario vignette (see Figure 5.4) shows how AM can enable direct interactions between forces deployed and ashore. Numerous similar scenarios can be envisioned for forward-deployed Marine units that possess 3D scanning and 3D printing capabilities.

Another innovative use of CC for expeditionary operations might be the autonomous construction of concrete UAV hangers to defend airfields and forward bases. A set of 8 or 12

[4] Contour Crafting needs to be part of logistics planning and battle-space preparation in the future.

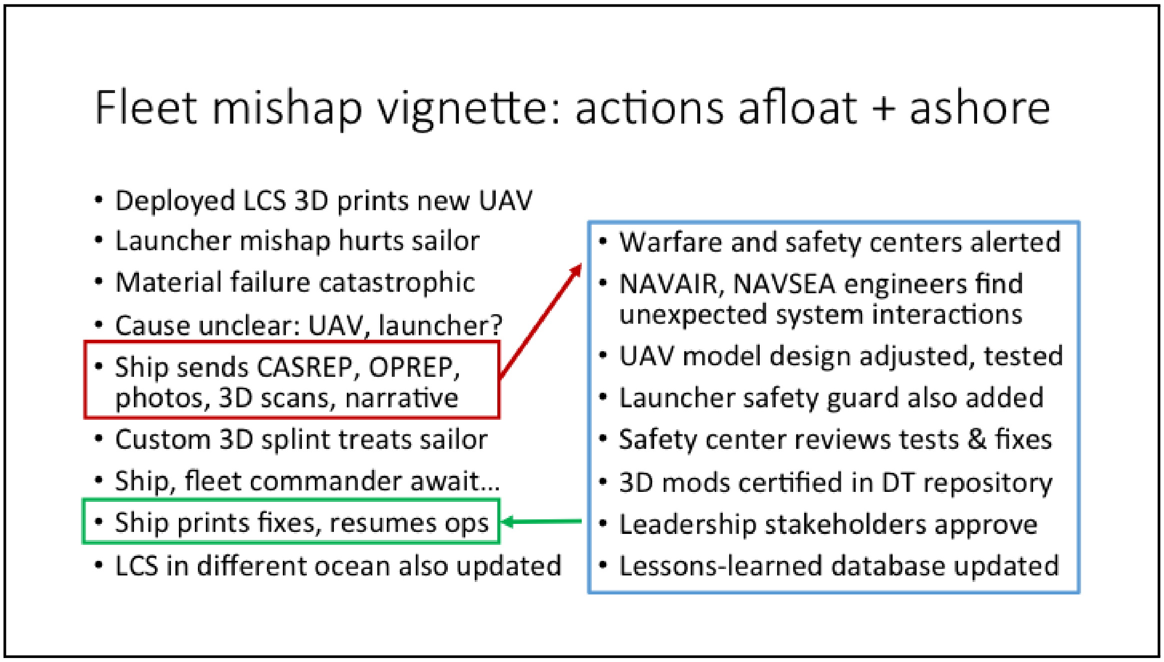

Figure 5.4: USMC and Navy Use of AM in a Distributed Environment. Source: [101]

UAVs might be programmed to surveil an airfield, in order to release or reduce the need for Marines to maintain a large in-person presence. Such a structure would be designed for robots instead of humans, containing diesel generator recharging capabilities along with local wireless networking, and remote uplink. In order to withstand small arms and mortar fire, such a concrete structure resembles a beehive in appearance and contains a small generator, fuel, docking, and repair stations for small surveillance and combat drones. Continuous video of the airfield provides an excellence way to provide physical security, and a concrete printer might then be used to fill bomb damage in the runway. This UAV sentry post is a force multiplier, enabling Marines to continue the fight forward while the UAVs hold already captured objectives. See Figure 5.5.

5.8 Summary

Chapter 5 discussed the potential uses, capabilities, and benefits of incorporating Contour Crafting into USMC and USN operations. Special attention was given to economic benefits of providing shelter to areas recently hit by natural disasters, or in general, crucial need, and also to risks and barriers associated with CC technology and integration of CC

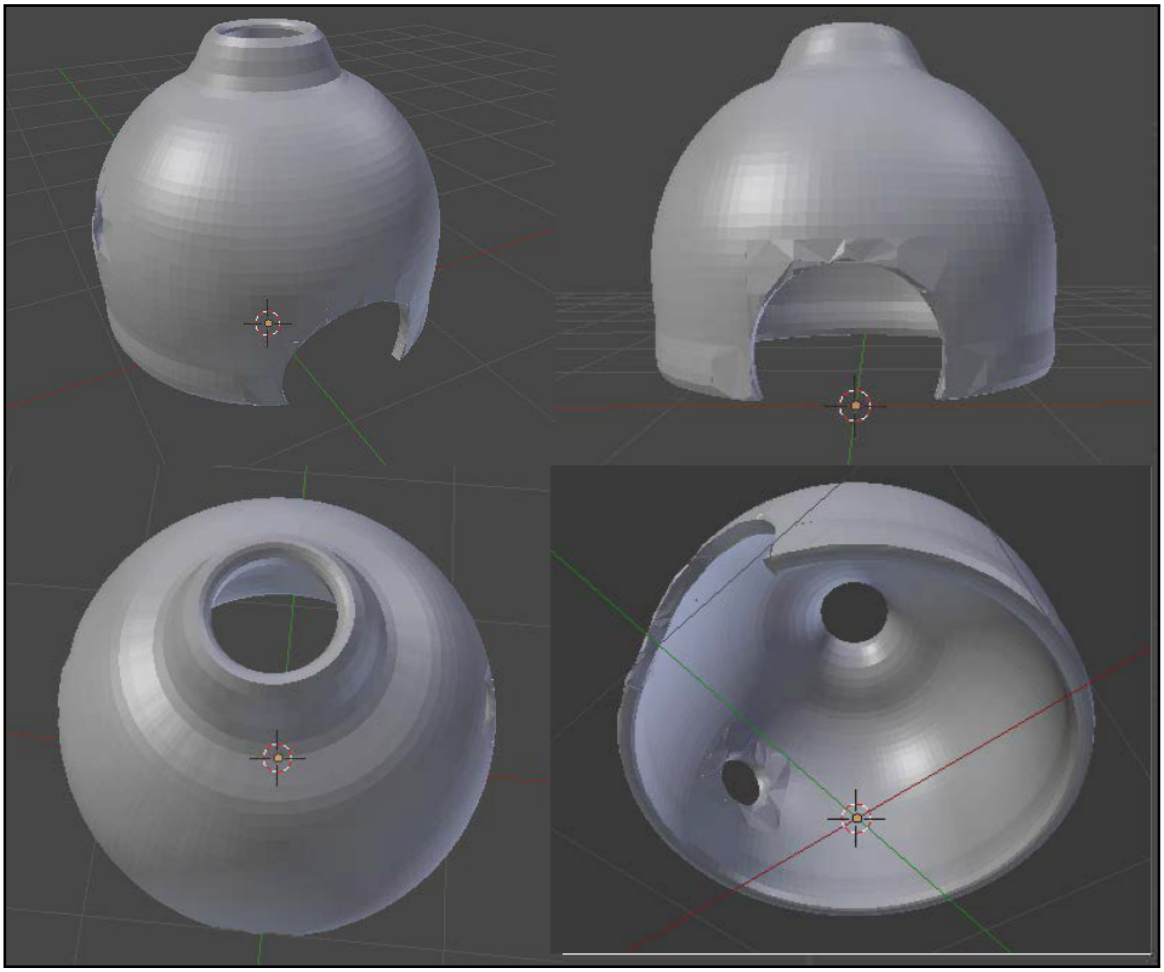

Figure 5.5: A Small Concrete UAV Hanger or Beehive Enables Autonomous and Continuous Over-watch and Security of Forward Airfields and Bases. Model made by the author.

in current force structure. Chapter 6 presents the thesis's case study interviewing 141 Marines and Sailors regarding their perspectives and ideas on AM technology adoption and implementation.

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CHAPTER 6:
Case Study: Survey on Current Adoption of Additive Manufacturing in USN and USMC

While Chapter 5 outlined potential benefits for the USMC and USN incorporation of Contour Crafting, Chapter 6 details the research goals, study design, execution, and results of a 2016 user study that involved select USMC and USN Seabee units. The design of the study was done over four months between September 2015 and January 2016. The main focus of the survey was to gauge Marines' and Sailors' views, opinions, and attitudes on new technologies, as well as their personal ownership and use of emerging technology with an emphasis on AM. Chapter 6 reviews the goals of the research, collection of data, the Institutional Review Board (IRB) process, and the study results.

6.1 Research Goals and Conduct of the Empirical Study

In order to acquire a comprehensive understanding of the adoption and diffusion of technology in the USMC and USN, a review was conducted of the technology and collection of objective data sets, and a survey was designed, aimed at collecting self-reported information from current and prospective users of AM technology. The ultimate goal of the empirical user study was to identify domain users' perspectives on different characteristics that may positively or adversely influence the adoption of AM in the USMC and USN. The study accomplished this by collecting a data set from current and prospective users; special emphasis was placed on the current state of adoption and use of digital technology, specifically on AM. Taking a survey of the entire USMC and USN would be the preferred method; however, the scale of that data collection effort was out of scope of this thesis. An alternative, a sampling of Marines and Seabees, was taken to best gauge the services on the aggregate. The communities that were approached and participated in the study represented a solid cross-section of the target populations.

6.2 Study Design

The technology survey was built after completing the research on different diffusion of innovation models, [32], [33], [81] and a thorough review of Pew Research Center studies focused on technology adoption. [73], [74] The type of questions listed in the final survey were purposely selected to provide a thorough understanding of the issues and topics that were identified as characteristic of prevailing models of diffusion of innovation.

The following groups of questions were identified and included in the final questionnaire:

- Demographics. The Demographics Section questions asked 6 questions pertaining to general information about the subject, such as age, rank, and MOS/rating.
- 3D Printing. The 3D Printing section questions asked 18 questions pertaining to current views, attitudes, and use of 3D printers and their associated technology, such as 3D scanners.
- User Attitudes. The User Attitudes section questions focused on user attitudes and how those are affected by media and other influences.
- Technology Use. The Technology Use section asked 22 questions pertaining to the use of different types of digital technology at the workplace by both the subject and their unit.
- Technology Owned. The Technology Owned section asked 17 questions pertaining to the types of digital technology owned and used personally by the subject at home.
- General Technology Questions. The General Technology section asked 8 questions pertaining to individual and family habits with respect to different types of digital technology.

Several questions were chosen to be identical to questions asked in studies done by the Pew Research Center, since one goal was to be able to compare the results of the Pew Research Center with data collected in this study. The following questions were in that group:

1. "Do you use the Internet or email, at least occasionally?"
2. "Now, I have a few questions about the future. Some books and movies portray a future where technology provides products and services that make life better for people. Others portray a future where technology causes environmental and social problems that make life worse for people. How about you: over the long term, do you

think that technological changes will lead to a future where people's lives are mostly better or to a future where people's lives are mostly worse?"
3. "Would you ride in a driverless car?"

The complete survey questionnaire can be found in Appendix A.

It was determined that an online survey (data collection) would be the best course of action, as it allowed us to reach a large number of individuals in a fairly short period of time, and it enabled Marines and Sailors to anonymously complete the survey whenever their schedules allowed for it.

6.3 Visit to Camp Pendleton and Port Hueneme

A visit to USMC Camp Pendleton and USN Base Port Hueneme was also organized as a part of the thesis research effort. Several meetings were conducted with USMC and USN leaders with the goal to become knowledgeable about their general views and opinions regarding AM and CC and to investigate potential uses in current service operations. Discussions with service representatives generated many insights that informed the design of the later survey.

For the use of AM, service representative ideas included printing molds to be used for the mass manufacture of parts and pieces in an austere environment, as well as the printing of modified parts or newly invented parts.

6.4 Subjects Pool

The final pool of subjects approached in this study consisted of the following groups:

- Navy Seabees
- USMC Engineers and other Marines attached to Engineer units

6.5 Methodology and Apparatus

6.5.1 Methodology

The gathering of data was conducted through an anonymous online survey. Each participant provided informed consent that indicated that they knew that they could terminate the survey at any point. Wording of the informed consent can be found in Appendix A. Data was collected using online LimeSurvey tools along with the LimeSurvey data analysis.

6.5.2 Apparatus

LimeSurvey was used as the apparatus to gather the survey data from the pool of subjects.

The data was stored on NPS servers; as agreed upon, the data collection was done anonymously with no stored personally identifiable information (PII). The subjects gave their informed consent at the beginning of the survey and were informed that they could opt out at any point during the survey. No compensation was given for their participation in the study.

A solicitation email was sent out to each pool of subjects to be distributed via the respective commands. The wording of the solicitation email can be found in Appendix A. The email was then resent two more times to each subject pool, in compliance with the IRB submission guidance, to encourage more participation in the survey.

6.6 Institutional Review Board Process

The Institutional Review Board (IRB) is used to protect human research subjects from any adverse effects of studies performed. Any research involving human subjects is vetted through the IRB committee.

The survey, along with supporting documents, (Appendix A) was submitted and approved by the NPS IRB Committee. A total of two amendments to the survey were also submitted and approved; each amendment had a request to engage additional subjects (units), also documented in Appendix A.

The following documents were included in the IRB approval package:

- IRB initial review application. This was the overarching IRB application and information page. It provided research basics, a research summary, subject population and recruitment, risks and benefits, data security and monitoring, and the principal investigator's statement of assurance.
- Email solicitation. This was the email to be sent to participants.
- Consent form. This was the form that informs the participants of their ability to terminate their participation in the survey at any time.
- Survey questions. This was the full listing of all survey questions.
- Email approval. This was the individual approval from each commander of the subject pools.
- Signed thesis proposal. This was the initial signed thesis proposal.
- IRB checklist. This was the IRB checklist on the conduct of human testing.

6.7 Summary

Chapter 6 provided details of the survey design regarding AM technology and technology in general in the USMC and USN, a review of specific question sets used in the survey, the selection of the subject pool, the methodology of the approach in executing the survey, as well as details of the IRB process and documents presented in the IRB package. Chapter 7 presents and discusses the results of the survey.

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CHAPTER 7:
Results and Discussion

While Chapter 6 detailed the process of the survey, Chapter 7 discusses the general results of the survey. Chapter 7 includes discussion of both the quantitative and qualitative results and provides a summary of collected data. Chapter 7 also contains discussion of the reasons behind certain data trends as compared to the findings of Pew research.

7.1 Demographics

A total of 120 individuals initiated the LimeSurvey online form. Twelve (12) individuals did not approve (accept) our informed consent, three (3) individuals approved informed consent but did not advance beyond that point, and six (6) individuals only entered the demographics data but withdrew right after that. This resulted in a total of 120 individuals who accepted informed consent, entered their demographics data and advanced with entering study data.

The demographics section of the survey is focused on defining characteristics of the respondents; specific wording of all questions can be found in Appendix A. Demographic questions included age, years of service in the military, identified gender, USMC military occupational specialty (MOS) or Navy enlisted classification (NEC) codes, rank, and attained education level. The results of the Demographics questions are summarized in Tables 7.1 through 7.5.

Table 7.1: Age of Survey Respondents

Age		
Age	Count	Percentage
18 - 21	11	9.17
22 - 30	35	29.17
31 - 40	54	45.00
41 - 50	16	13.33
51 and over	4	3.33
Totals	120	100.00

Table 7.2: Years of Military Service

Years of Military Service		
Number of Years	Count	Percentage
1 - 4	28	23.33
5 - 8	25	20.85
9 - 12	17	14.17
13 - 16	12	10.00
17 - 20	20	16.67
21+	18	15.00
Totals	120	100.00

Table 7.3: Gender

Gender		
Gender	Count	Percentage
Female	18	15.00
Male	102	85.00
Totals	120	100.00

Table 7.4: Rank

Military Rank		
Rank	Count	Percentage
E1 - E3	9	7.50
E4 - E5	19	15.83
E6 - E-9	29	24.17
WO - CWO5	6	5.00
O1 - O3	42	35.00
O4 - O6	15	12.50
Totals	120	100.00

Table 7.5: Education Level

Education Level		
Education Level	Count	Percentage
High school diploma or equivalent	25	20.83
Partial work toward associates degree	24	20.00
Associates degree	4	3.33
BS / BA	36	30.00
Partial work toward masters	10	8.33
Masters degree	21	17.50
Any education beyond masters degree	0	0.00
Totals	120	100.00

Demographics help provide insight into a target population. The largest group of respondents was aged 31-40 (45%), had been in the military for 1-4 years (23.33%), were male (85%), were company grade O1-O3 (35%), and had completed a BS or BA (30%). These responses make sense and offer a good representation of the USMC and USN on the whole. More female responses would give a more balanced percentage, but with USMC combat engineer only recently opening to females, it is understandable that this number is lower than the general aggregate military population.

7.2 Additive Manufacturing Questions

The additive manufacturing questions focused specifically on AM and the respondents' knowledge of AM technology. As expected, most had some knowledge of AM with 85% agreeing that they know what 3D printing is. Most thought that AM has great potential both at home and within their work spaces with 74% and 70% agreeing, respectively. Tables 7.6 through 7.17 summarize the results of the survey's additive manufacturing questions.

Table 7.6: 3D Printing Knowledge

"I know what 3D printing is."		
Level	Count	Percentage
Strongly disagree	3	2.50
Disagree	3	2.50

Continuation of Table 7.6		
Level	Count	Percentage
Somewhat disagree	4	3.33
Neither agree or disagree	8	6.67
Somewhat agree	20	16.67
Agree	43	35.83
Strongly agree	39	32.50
Totals	120	100.00

Table 7.7: AM Potential in the Home

"I think AM has great potential for home use."		
Level	Count	Percentage
Strongly disagree	2	1.67
Disagree	4	3.33
Somewhat disagree	7	5.83
Neither agree or disagree	18	15.00
Somewhat agree	27	22.50
Agree	37	30.83
Strongly agree	25	20.83
Totals	120	100.00

In Table 7.8, the percentage of people that agree in some form that AM has great potential in their work environment is 70%, potentially indicating a high level of confidence in the technology.

Table 7.8: AM Potential in the Military Domain

"I think AM has great potential in my work environment (military domain)."		
Level	Count	Percentage
Strongly disagree	4	3.33
Disagree	2	1.67
Somewhat disagree	8	6.67
Neither agree or disagree	22	18.33

Continuation of Table 7.8		
Level	Count	Percentage
Somewhat agree	32	26.67
Agree	23	19.17
Strongly agree	29	24.17
Totals	120	100.00

Table 7.9: AM Personal Use

"I currently have and use some 3D printed items myself."		
Owns and Uses 3D Printed Items	Count	Percentage
Yes	3	2.50
No	117	97.50
Totals	120	100.00

If the respondent answered "yes" to the question in Table 7.9, another question was then posed. What are those items? Answers follow:

- kids' toys
- bottle stoppers
- artwork
- aircraft parts (Turbines, metal sintered)
- plastic prototypes

Table 7.10: AM Use at Work

"Our unit currently has and uses some 3D printed items."		
Unit Owns and Uses 3D Printed Items	Count	Percentage
Yes	4	3.33
No	116	96.67
Totals	120	100.00

If the respondent answered "yes" to the question in Table 7.10, another question was then posed. What are those items? Answers follow:

- MGB Model Set for Bridge Training
- maintenance shop
- welding shop
- ordnance
- stuck round tools
- terrain models

This is where the experience with AM decreases. Even though Marines and Sailors think that there is a great potential, only 2.50% and 3.33% of those surveyed use AM parts or pieces either in their house or at work, respectively. This again is in contrast to the belief that AM could do great things, with 40.83% of respondents indicating that they think a house could be 3D printed within the next 10 years. 41.67% said that, if given a AM capability at work, they could use it immediately to make their work more efficient and 55% suggested that some parts used at their units could be 3D printed, which speaks to the promise and potential that AM has brought with it in recent years.

Table 7.11: AM to Build a House in Next 10 Years

"I think that a house could be 3D printed in the next 10 years."		
House Could be 3D Printed	Count	Percentage
Yes	49	40.83
No	24	20.00
I don't know	47	39.17
Totals	120	100.00

Table 7.12: AM Capability at Work

"If given a 3D printing capability at work, I could use it immediately to make my workplace more efficient."		
Level	Count	Percentage
Strongly disagree	5	4.17
Disagree	13	10.83
Somewhat disagree	9	7.50
Neither agree or disagree	43	35.83
Somewhat agree	17	14.17

Continuation of Table 7.12		
Level	Count	Percentage
Agree	18	15.00
Strongly agree	15	12.50
Totals	120	100.00

Table 7.13: Current AM Capability at Work

"To my knowledge, my unit does have a 3D printing capability."		
Unit Has 3D Printing Capability	Count	Percentage
Yes	5	4.17
No	84	70.00
I don't know	15	12.50
No answer	16	13.33
Totals	120	100.00

Data set presented in Tables 7.12 - 7.14 suggests that only 4.17% have an AM capability at work, and that 55% of unit members believe that they could make parts with AM technology in their place of work (if they had 3D printing capability available at the workplace.)

Table 7.14: Perception of Current AM capability

"Given my knowledge of AM, I believe that some parts used by our unit could be made via AM."		
Some Parts Could Be Made via AM	Count	Percentage
Yes	66	55.00
No	18	15.00
I don't know	36	30.00
Totals	120	100.00

Table 7.15: USMC and Navy AM Use

"I am aware that the Navy and USMC are both pursuing 3D printing technology."		
Aware of Navy and USMC AM Initiative	Count	Percentage
Yes	59	49.17
No	60	50.00
No answer	1	0.83
Totals	120	100.00

Table 7.16: USMC Is Quick to Adopt New Technology

"I think the USMC Is quick to adopt new technology."		
USMC Is Quick to Adopt New Technology	Count	Percentage
Yes	43	35.83
No	76	63.33
No answer	1	0.83
No response	0	0
Totals	120	100.00

Data presented in Table 7.15 suggests that more respondents perceive the USN to be quick at adopting new technology (54.17%), and 35.83% of subjects see the USMC as being quick to adopt new technology. results presented in Table 7.15, indicate that 49.17% of respondents are aware of the USMC and USN efforts in AM.

Table 7.17: U.S. Navy Is Quick to Adopt New Technology

"I think the U.S. Navy Is quick to adopt new technology."		
Navy Is Quick to Adopt New Technology	Count	Percentage
Yes	65	54.17
No	54	45.00
No answer	1	0.83
No response	0	0
Totals	120	100.00

7.3 Future Technology

The survey included two questions that were also posed in a 2014 Pew study [13]. The Pew data is visualized in Figure 7.2. The Pew research shows that 59% of people have a positive view of technology in the future [13]. Our survey suggests that 55.83% of respondents - USMC and USN personnel - have a positive view of future technology. At this point, it is hard to speculate about the reason for difference in opinions between general public and USMC and USN personnel. The views on Future Technology are summarized in Tables 7.18 and 7.19 and graphed in Figure 7.1.

Table 7.18: View of Future Technology

"Now, I have a few questions about the future. Some books and movies portray a future where technology provides products and services that make life better for people. Others portray a future where technology causes environmental and social problems that make life worse for people. How about you? Over the long term, you think that technological changes will lead to a future where people's lives are mostly better or to a future where people's lives are mostly worse?"		
Effect of Technology on People's Lives	Count	Percentage
Mostly better	67	55.83
Mostly worse	17	14.17
Don't know	25	20.83
No answer	10	8.33
Refuse to answer	1	0.83
Totals	120	100.00

The next question asked specifically about the use of driverless cars. In the Pew Research Center survey, 48% of respondents would want to ride in a driverless car compared to the 55% of the USMC and USN units that would do the same. This difference may be because of greater use of UAVs in the military as compared to civil use. The military has used UAVs for decades and have come to use them in everyday combat operations. This familiarity with UAVs may be the reason the USMC and USN respondents are more comfortable with the idea of a driverless car, but it is hard to make any conclusion without probing this topic with additional questions.

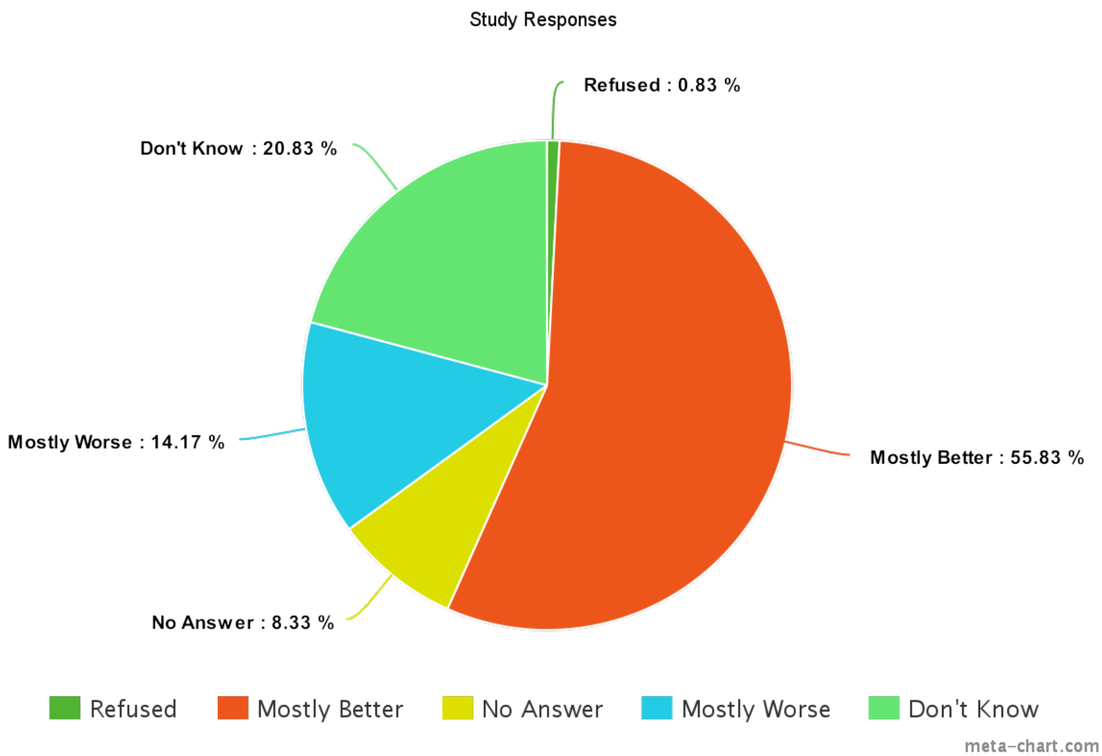

Figure 7.1: USMC and USN Responses

Table 7.19: Driverless Car Use

"Would you ride in a driverless car?"		
Ready to Use Driverless Car	Count	Percentage
Yes	55	45.83
No	45	37.50
Don't know	16	13.33
No response	2	1.67
Refuse to answer	2	1.67
Totals	120	100.00

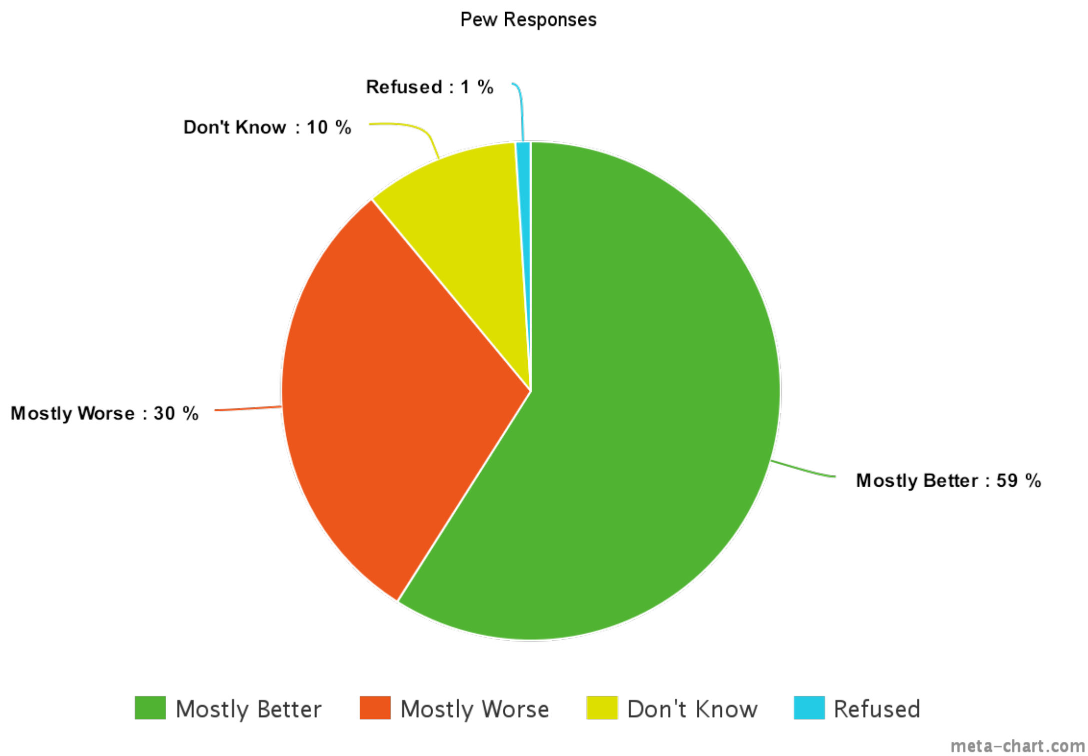

Figure 7.2: Pew Future Technology Responses. Adopted From: [13]

7.4 General Technology Use

With respect to the general use of technology, it is observed that the survey respondents mostly identify themselves as early adopters with some people identifying themselves as innovators. The early adopters are then able to have a more wait and see attitude when adopting the newer technology. Respondents stay well informed of current technological trends as shown in Tables 7.20, 7.21, 7.23, 7.24, 7.25 and 7.26. This may be because of their younger age and greater use of sites such as Facebook, as shown in Section 7.5. The general technology use results also show that endorsement from leaders plays a large role in a person choosing to adopt a non-mandatory piece of technology. Users are generally very efficient at using technology, not requiring outside help to use their technology. Units are neither quick nor slow to adopt new technology. Current views of new technology is in general positive by the units as a whole.

Table 7.20: Technology Purchased

"I am among the first ones who purchase and use examples of new technology when they become available."		
Level	Count	Percentage
Strongly disagree	7	5.83
Disagree	27	22.50
Somewhat disagree	24	20.00
Neither agree or disagree	19	15.83
Somewhat agree	23	19.17
Agree	12	10.00
Strongly agree	4	3.33
No answer	4	3.33
Totals	120	100.00

Table 7.21: Technology Seeking

"I always actively look for information about new technology that I could use."		
Level	Count	Percentage
Strongly disagree	5	4.17
Disagree	22	18.33
Somewhat disagree	18	15.00
Neither agree or disagree	17	14.17
Somewhat agree	18	15.00
Agree	27	22.50
Strongly agree	9	7.50
No answer	4	3.33
Totals	120	100.00

Table 7.22: Technology Seeking for Unit

"I always actively look for information about new technology that our unit could use."		
Level	Count	Percentage
Strongly disagree	14	11.67
Disagree	16	13.33
Somewhat disagree	12	10.00
Neither agree or disagree	22	18.33
Somewhat agree	18	15.00
Agree	26	21.67
Strongly agree	8	6.67
No answer	4	3.33
Totals	120	100.00

Table 7.23: Technology Seeking for Self

"I keep myself well informed about current and future technologies that I could use."		
Level	Count	Percentage
Strongly disagree	2	1.67
Disagree	12	10.00
Somewhat disagree	16	13.33
Neither agree or disagree	17	14.17
Somewhat agree	37	30.83
Agree	23	19.17
Strongly agree	9	7.50
No answer	4	3.33
Totals	120	100.00

Table 7.24: Technology Seeking for Unit

"I keep myself well informed about current and future technologies that our unit could use."		
Level	Count	Percentage
Strongly disagree	8	6.67

Continuation of Table 7.24		
Level	Count	Percentage
Disagree	10	8.33
Somewhat disagree	10	8.33
Neither agree or disagree	30	25.00
Somewhat agree	32	26.67
Agree	23	19.17
Strongly agree	3	2.50
No answer	4	3.33
Totals	120	100.00

Table 7.25: Technology Purchases

"I am among the last ones who buy and tryout examples of new technology."		
Level	Count	Percentage
Strongly disagree	9	7.50
Disagree	29	24.17
Somewhat disagree	26	21.67
Neither agree or disagree	21	17.50
Somewhat agree	15	12.50
Agree	10	8.33
Strongly agree	6	5.00
No answer	4	3.33
Totals	120	100.00

The data presented in Tables 7.25, 7.26, 7.27, and 7.28 indicate that respondents will, in general, wait for a technology to catch on, with 54.17% agreeing to some degree of waiting to see if a technology will catch on before actually purchasing it (Table 7.25). The respondents also agree that they are more likely to use a technology if their peers recommend it to them (Table 7.26). Respondents also agree that they would recommend a new technology to their peers outside of work with 45.67% agreeing. This is similar to those who advertise or endorse technology at work (Table 7.29), with 61.67% indicating that they agree that they would endorse a technology at work.

Table 7.26: Technology Popularity

"I like to wait to see if new technology catches on first before I buy it for myself."		
Level	Count	Percentage
Strongly disagree	5	4.17
Disagree	11	9.17
Somewhat disagree	9	7.50
Neither agree or disagree	26	21.67
Somewhat agree	29	24.17
Agree	27	22.50
Strongly agree	9	7.50
No answer	4	3.33
Totals	120	100.00

Table 7.27: Technology Recommendations from Peers

"I am more likely to use a new technology if my peers recommend it to me."		
Level	Count	Percentage
Strongly disagree	4	3.33
Disagree	8	6.67
Somewhat disagree	10	8.33
Neither agree or disagree	18	15.00
Somewhat agree	42	35.00
Agree	27	22.50
Strongly agree	6	5.00
No answer	5	4.17
Totals	120	100.00

Table 7.28: Technology Recommendations to Peers

"I am very likely to promote and advertise some technology among my peers outside of work."		
Level	Count	Percentage
Strongly disagree	4	3.33

Continuation of Table 7.28		
Level	Count	Percentage
Disagree	11	9.17
Somewhat disagree	10	8.33
Neither agree or disagree	34	28.33
Somewhat agree	26	21.67
Agree	25	20.83
Strongly agree	5	4.17
No answer	5	4.17
Totals	120	100.00

Table 7.29: Technology Recommendations at Work

"I am very likely to promote and advertise some technology that we could use at work."		
Level	Count	Percentage
Strongly disagree	3	2.50
Disagree	6	5.00
Somewhat disagree	5	4.17
Neither agree or disagree	27	22.50
Somewhat agree	35	29.17
Agree	33	27.50
Strongly agree	6	5.00
No answer	5	4.17
Totals	120	100.00

Table 7.30: Technology Use of Leaders

"If my leadership uses some technology, I am more likely to try it myself."		
Level	Count	Percentage
Strongly disagree	5	4.17
Disagree	9	7.50
Somewhat disagree	4	3.33
Neither agree or disagree	33	27.50
Somewhat agree	29	24.17

Continuation of Table 7.30		
Level	Count	Percentage
Agree	31	25.83
Strongly agree	4	3.33
No answer	5	4.17
Totals	120	100.00

Table 7.31: Technology Endorsement of Leaders

"If my leadership endorses some technology that is not mandatory, but it could be useful for our unit, I am more likely to try it."		
Level	Count	Percentage
Strongly disagree	3	2.50
Disagree	1	.83
Somewhat disagree	4	3.33
Neither agree or disagree	25	20.83
Somewhat agree	37	30.83
Agree	40	33.33
Strongly agree	5	4.17
No answer	5	4.17
Totals	120	100.00

Table 7.32: Technology Endorsement of Leaders

"If our leaders endorse some technology that is not mandatory but it could be useful for our unit, our unit is more likely to use it."		
Level	Count	Percentage
Strongly disagree	3	2.50
Disagree	5	4.17
Somewhat disagree	10	8.33
Neither agree or disagree	26	21.67
Somewhat agree	34	28.33
Agree	32	26.67
Strongly agree	5	4.17

Continuation of Table 7.32		
Level	Count	Percentage
No answer	5	4.17
Totals	120	100.00

Table 7.33: Technology Use, Mandatory

"I am not likely to use new technology at work until it is mandatory."		
Level	Count	Percentage
Strongly disagree	7	5.83
Disagree	38	31.67
Somewhat disagree	25	20.83
Neither agree or disagree	25	20.83
Somewhat agree	14	11.67
Agree	4	3.33
Strongly agree	2	1.67
No answer	5	4.17
Totals	120	100.00

Table 7.34: Technology Use of Unit, Mandatory

"Our unit is not likely to use some technology until it is mandatory."		
Level	Count	Percentage
Strongly disagree	3	2.50
Disagree	20	16.67
Somewhat disagree	13	10.83
Neither agree or disagree	32	26.67
Somewhat agree	23	19.17
Agree	14	11.67
Strongly agree	10	8.33
No answer	5	4.17
Totals	120	100.00

Table 7.35: Technology Use, Efficiency

"I consider myself to be very efficient at using technology. Efficient is defined as performing a task more quickly and with better precision than an average person."		
Level	Count	Percentage
Strongly disagree	2	1.67
Disagree	6	5.00
Somewhat disagree	7	5.83
Neither agree or disagree	23	19.17
Somewhat agree	41	34.17
Agree	28	23.33
Strongly agree	8	6.67
No answer	5	4.17
Totals	120	100.00

Table 7.36: Technology Help at Work

"I have someone who helps me on a regular basis with technology that I use at work."		
Level	Count	Percentage
Strongly disagree	18	15.00
Disagree	31	25.83
Somewhat disagree	13	10.83
Neither agree or disagree	23	19.17
Somewhat agree	18	15.00
Agree	10	8.33
Strongly agree	2	1.67
No answer	5	4.17
Totals	120	100.00

Table 7.37: Technology Recommendation in Unit

"I am responsible for recommending new technology in my unit."		
Level	Count	Percentage
Strongly disagree	24	20.00

Continuation of Table 7.37		
Level	Count	Percentage
Disagree	30	25.00
Somewhat disagree	11	9.17
Neither agree or disagree	31	25.83
Somewhat agree	17	14.17
Agree	1	0.83
Strongly agree	1	0.83
No answer	5	4.17
Totals	120	100.00

Table 7.38: Technology Recommendations for Purchase

"I am responsible for making final decision regarding the purchase of some new technology in our unit."		
Responsible for Unit Decisions	Count	Percentage
Yes	9	7.50
No	106	88.33
No answer	5	4.17
Totals	120	100.00

Table 7.39: Technology Acquisition of Unit

"When compared to other units, our unit is among the first ones to acquire and use new technology."		
Level	Count	Percentage
Strongly disagree	18	15.00
Disagree	28	23.33
Somewhat disagree	12	10.00
Neither agree or disagree	35	29.17
Somewhat agree	16	13.33
Agree	5	4.17
Strongly agree	1	.83
No answer	5	4.17

Continuation of Table 7.39		
Level	Count	Percentage
Totals	120	100.00

Table 7.40: Technology Attitude of the Unit

"My unit, on the whole, has a favorable attitude toward new technology."		
Level	Count	Percentage
Strongly disagree	2	1.67
Disagree	6	5.00
Somewhat disagree	9	7.50
Neither agree or disagree	48	40.00
Somewhat agree	25	20.83
Agree	21	17.50
Strongly agree	4	3.33
No answer	5	4.17
Totals	120	100.00

7.5 Technology Use at Home and at Work

A person's use of technology at home can greatly effect their use at work and therefore, help to see how and why they use that technology. The Technology Use at Home and at Work results show that most respondents use a computer daily both at work and at home. As shown in Table 7.45, 58.33 % have at least two computers at home, with 6.67% owning 5 or more computers shown in Table 7.45. Smartphone use is almost saturated with all respondents owning at least one smartphone at home, shown in Table 7.46. Tables 7.41 through 7.61 summarize the results of the Technology Use at Home and at Work survey questions.

Table 7.41: Computer Use at Home

"Estimate the average time you use a computer at home."		
Frequency of Use	Count	Percentage
Daily	81	67.50

Continuation of Table 7.41		
Frequency of Use	Count	Percentage
Weekly	18	15.00
Monthly	3	2.50
Rarely	8	6.67
Do not use	0	0.00
No answer	10	8.33
Totals	120	100.00

Table 7.42: Computer Use at Work

"Estimate the average time you use a computer at work."		
Frequency of Use	Count	Percentage
Daily	107	89.17
Weekly	2	1.67
Monthly	0	0.00
Rarely	2	1.67
Do not use	0	0.00
No answer	9	8.33
Totals	120	100.00

Table 7.43: Computers Owned at Home

"How many computers, both desktop and laptop are in your household?"		
Number of Computers at Home	Count	Percentage
0	3	2.50
1	30	25.00
2	40	33.33
3	20	16.67
4	10	8.33
5+	8	6.67
No answer	9	7.50
Totals	120	100.00

Table 7.44: Computers Owned and Used at Home

"How many of those computers do you actively use yourself?"		
Number of Computers Personally Used	Count	Percentage
0	4	3.33
1	65	54.17
2	30	25.00
3	9	7.50
4	0	0.00
5+	2	1.67
No answer	10	8.33
Totals	120	100.00

Table 7.45: Smartphones Owned

"How many smartphones are in your household?"		
Number of Smartphones	Count	Percentage
0	0	0.00
1	20	16.67
2	55	45.83
3	17	14.17
4	6	5.00
5+	13	10.83
No answer	9	7.50
Totals	120	100.00

Table 7.46: Smartphones Used

"How many of those smartphones do you actively use yourself?"		
Number of Smartphones	Count	Percentage
0	0	0.00
1	101	84.17
2	8	6.67
3	1	0.83

Continuation of Table 7.46		
Number of Smartphones	Count	Percentage
4	0	0.00
5+	1	.83
No answer	9	7.50
Totals	120	100.00

Regarding the time of ownership from actually buying their first smartphone, respondents overwhelmingly (62.50%) purchased their first smartphone five or more years ago, shown in Table 7.47, demonstrating the familiarity that people now have for and overall satisfaction of smartphones.

Table 7.47: Smartphones Purchase History

"How long ago did you buy your first smartphone?"		
Number of Years	Count	Percentage
1 year	2	1.67
2 years	9	7.50
3 years	9	7.50
4 years	15	12.50
5+ years	75	62.50
No answer	10	8.33
Totals	120	100.00

With respect to gaming consoles, the data suggests that the majority of households do own at least one gaming console, with 65.83% of respondents suggesting that they own 1 or more such devices. This is interesting because only 49.17% indicate they actually use the console. One can only assume that their children or roommates are the ones using the console.

Table 7.48: Gaming Consoles Owned

"How many gaming consoles are in your household, working or not?"		
Number of Gaming Consoles at Home	Count	Percentage
0	31	25.83
1	31	25.83
2	17	14.17
3	15	12.50
4	8	6.67
5+	8	6.67
No answer	10	8.33
Totals	120	100.00

Table 7.49: Gaming Consoles Use

"How many of those gaming consoles do you actively use yourself?"		
Number of Gaming Consoles Personally Used	Count	Percentage
0	49	40.83
1	37	30.83
2	12	10.00
3	6	5.00
4	3	2.50
5+	1	0.83
No answer	12	10.00
Totals	120	100.00

Table 7.50: Internet and Email Use

"Do you use the internet or email, at least occasionally?"		
Use of Internet or Email	Count	Percentage
Yes	108	90.00
No	2	1.67
No answer	10	8.33
Totals	120	100.00

Table 7.51 shows a comparison to the Pew results (mentioned in [13]) regarding use among respondents of email and internet. Here, 90% use the internet or email at least occasionally compared to almost 85% of Pew responses.

Table 7.51: Internet and Email Use on Mobile Device

"Do you access the internet on a cell phone, tablet or other mobile handheld device, at least occasionally?"		
Mobile Device	Count	Percentage
Cell Phone	108	90.00
Tablet	67	55.83
Other hand-held device	18	15.00
No answer	6	5.00
Totals	120	100.00

Table 7.52: Smartphone Use and Frequency

"If you do have a smartphone, how often do you check your smartphone for updates (calls, messages or notifications)?"		
Frequency of Checking	Count	Percentage
Less than once a day	3	2.50
About once per day	6	5.00
A few times per day	38	31.67
About once per hour	20	16.67
A few times per hour	32	26.67
Every few minutes	12	10.00
No answer	9	7.50
Totals	120	100.00

In the video quality choice, respondents overwhelmingly (70.83%) chose high definition video to view videos. This can help leaders to decide to invest in higher quality training videos to keep the interest of viewers longer.

Table 7.53: Video Quality Choice at Home

"When faced with the choice of High Definition/Standard Definition video quality, which do you choose at home? Example: streaming video from specialized video-on-demand service like Netflix."		
Video Quality Watched	Count	Percentage
HD	85	70.83
SD	12	10.00
I do not watch video using the internet or streaming	7	5.83
No answer	16	13.33
Totals	120	100.00

Table 7.54: Video Quality Choice on Mobile Devices

"When faced with the choice of High Definition/Standard Definition video quality, which do you choose on mobile? Example: streaming video from specialized video-on-demand service like Netflix."		
Video Quality Watched	Count	Percentage
HD	63	52.50
SD	23	19.17
I do not watch video on mobile	20	16.67
No answer	14	11.67
Totals	120	100.00

In Table 7.55, email is the highest used application followed by Facebook and news sites. If leaders are keen to advertise their new and emerging technologies to users, they would be wise to use new techniques that exploit respondents' use of those particular applications.

Table 7.55: Frequently Used Applications and Websites

"What are your frequently used applications/visited websites?"		
Application	Count	Percentage
Facebook	75	62.50
Twitter	7	5.83
Snapchat	21	17.50

Continuation of Table 7.55		
Application	Count	Percentage
Instagram	25	20.83
Email	100	83.33
Youtube	63	52.50
News Sites	73	60.83
Blogs	13	10.83

In Table 7.56, the persistence of the use of hard copies of books still prevails over digital versions. This would help to decide to invest in libraries to allow users their preferred method of book use.

Table 7.56: Book Use

"I prefer to read a hard copy of the book rather than read digital version of the same book."		
Level	Count	Percentage
Strongly disagree	9	7.50
Disagree	7	5.83
Somewhat disagree	6	5.00
Neither agree or disagree	15	12.50
Somewhat agree	20	16.67
Agree	23	19.17
Strongly agree	27	22.50
No answer	13	10.83
Totals	120	100.00

Table 7.57: Technology Used at Home on Daily Basis

"Select all types of technology that apply to your regular daily activity at home."		
Technology Used Daily at Home	Count	Percentage
Computer	92	76.67
Tablet	53	44.17
Smartwatch	34	28.33
Cell phone	109	90.83

Continuation of Table 7.57		
Technology Used Daily at Home	Count	Percentage
Virtual reality system	1	0.83
3D printer	2	1.67

Table 7.58: Technology Used at Work on Daily Basis

"Select all types of technology that apply to your regular daily activity at your workplace."		
Technology Used Daily at Work	Count	Percentage
Computer	108	90.00
Tablet	16	13.33
Smartwatch	18	15.00
Cell phone	85	70.83
Virtual reality system	1	0.83
3D printer	1	0.83

Here, users respond that they are very flexible when it comes to learning a new technology, with most disagreeing that they would give up on learning a new technology after 15 minutes of attempting and learning the new technology. Leaders can therefore build their lessons around the idea that users and learners have a somewhat elastic attention span.

Table 7.59: Learning New Technology

"If it takes more than 15 minutes to learn a new technology, I give up on it and continue doing things the way I did prior to attempting the new technology, e.g. ordering a pizza via telephone or ordering pizza through an app."		
Level	Count	Percentage
Strongly disagree	27	22.50
Disagree	34	28.33
Somewhat disagree	18	15.00
Neither agree or disagree	14	11.67
Somewhat agree	9	7.50
Agree	5	4.17
Strongly agree	2	1.67

Continuation of Table 7.59		
Level	Count	Percentage
No answer	11	9.17
Totals	120	100.00

Table 7.60: New Technology at Work

"How many new systems has your unit adopted and used in the past three years; a system is defined as any combination of different types of technology used to increase the efficiency (productiveness) of you or any part of your unit?"		
Number of New Systems	Count	Percentage
0	26	21.67
1	11	9.17
2	8	6.67
3	9	7.50
4	2	1.67
5	2	1.67
6+	1	0.83
No answer	61	50.83
Totals	120	100.00

Table 7.61: Smartphone Application Installations

"How many new software applications did you install on your smartphone (past year)?"		
Number of New Apps. Installed	Count	Percentage
1	6	5.00
2	10	8.33
3	7	5.83
4	10	8.33
5	15	12.50
6	2	1.67
7	8	6.67
8	5	4.17
9	1	0.83

Continuation of Table 7.61		
Number of New Apps. Installed	Count	Percentage
10	34	28.33
No answer	43	18.33
Totals	120	100.00

The question presented in Table 7.58, asked about the number of new software applications that users installed on their smartphones during last year. 28.33% of surveyed individuals responded that they have downloaded over 10 new applications on their smartphones. This information can serve as a testimony of frequency of use as well as technical skills that individuals/users have (they installed that software themselves). This, in turn, can encourage delivering some work-related applications and training modules via smartphone applications.

7.6 Summary

Chapter 7 presented and discussed the data collected in online survey from the USMC and USN active duty respondents. Chapter 8 finalizes the work of this thesis by providing overall suggestions and potential for the incorporation of AM into USMC and USN operations.

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CHAPTER 8:
Conclusion

While Chapter 7 detailed survey results, Chapter 8 summarizes the main suggestions and possibilities for incorporation of AM into USMC and USN operations and also discusses the main contributions of the conducted survey to the larger body of knowledge.

8.1 Main Conclusion

When studying an emerging and potentially disruptive technology that is of great interest in a given application domain, important pieces of the puzzle include understanding the users' familiarity with and perception of the usefulness of that technology, as well as the adoption rate (that reflects the rate at which technology diffuses into the fabric of that user group). With respect to AM, the data suggests that current ownership and use of 3D printers is extremely low among USMC and USN respondents. This is in contrast with the perceived potential that this type of technology has in the eyes of respondents for their homes and workplaces. The perceived value of AM and the potential of using it in the workplace are positive indicators of increase future adoption. After reviewing the responses collected in this survey, the inclusion of AM in current and future operations seems to provide a very solid basis for earning a lasting and permanent place. The analysis of a variety of application domains indicates that the most immediate benefits of AM for the USN and USMC may come from reverse engineering and the production of parts. The situations best served are the cases when: parts are expensive to procure or to produce in given circumstances, they cannot be acquired by traditional means, or the time within which the unit needs to acquire them is extremely short and any unnecessary delay caused by traditional procurement and production would significantly impact the unit's operational readiness.

The analysis of collected data suggests that technology use is widespread; this is especially the case with regard to affordable commercial off-the-shelf (COTS) examples of digital technology solutions commonly used by a large number of users. Selected data sets presented in Pew Research Center reports are compared with the data collected in this thesis's; the comparison suggests a similarity between a military audience and a general population. When it comes to the actual use of AM technology, it seems that though Marines

and Sailors think that AM technology has great potential for use in current operations, at this point less than two percent actually own a 3D printer in their homes. While more data should be collected to discern the reasons for this, even now, the perceived potential being so high while 3D device ownership is so low indicates that adoption of AM technology is still in its early stage. The sheer potential of AM as demonstrated by Marines and Sailors calls for greater investigation into the best strategies for promoting AM technology, providing incentives for its widespread use, and leveraging it in the USMC and USN domains.

The use of AM, especially its CC form, in expeditionary and amphibious operations is immediately relevant and useful. Even though current use remains low in the USMC and USN, leader endorsement of AM in the context of expeditionary manufacturing will help to bring about the much discussed third offset strategy [102]. The need for distributed and efficient logistics will become a force multiplier in which the U.S. will continue to dominate the asymmetric battlefield.

8.2 Conclusions Regarding Research Questions

This thesis has set out to answer the following research questions:

1. Does Additive Manufacturing, in its current and future form, have the potential to significantly add to the capabilities of the Marine Corps? What elements of the Digital Thread and Digital Twin would need to be addressed in order to fully integrate additive manufacturing technologies into Marine Corps operations?
    - As discussed in detail in this thesis, new AM processes and materials are developed daily. Distributed manufacturing and resupply is now possible.
    - As evidenced by the U.S. Army Rapid Equipping Force and their many examples of successful development of expeditionary parts in both Iraq and Afghanistan, expeditionary manufacturing has a place in current and future USMC and USN operations.
    - As revealed in Chapter 3 and 5, there exists the potential for an array of application domains that would benefit from the use of AM. This potential ranges from printing small parts (a replacement shower drain, consumable elements of UAVs), to large scale objects like shelters and fortifications.
    - With the introduction of AM in the USMC and USN, the use of secure yet open

use of digital watermarking, two step authentication, 3D model standards, and efficient data-basing will need to be evaluated.

2. What types of scenarios and use cases will benefit most from the application of additive manufacturing?
    - Replacement parts for legacy systems is a prime area for exploitation of AM. Using examples such as the BV-206 and USMC Amphibious Assault Vehicle, low production run parts could be easily reverse engineered and placed into use, extending the life of these pieces of equipment.
    - When a part is needed in a remote or austere environment such as aboard a ship or at a distant forward operating base, printing the much needed part may be the only or least costly option available.
    - With use of Contour Crafting and CC technology in USMC expeditionary operations, the USMC and USN, along with the Department of State, would be able to expand their HADR capabilities in order to help countries recover from and thrive after disasters. This type of deployment of AM technology has the potential to positively expand the U.S. sphere of influence and help win hearts and minds across the world.
    - Expeditionary manufacturing laboratories consist of AM machines but also include CNC, milling, injection molding, vacuum molding, and electronics manufacturing equipment, would be staffed by sailors and Marines along with manufacturing experts. Laboratories would cut logistics lines, saving time, fuel, and lives in the process.
3. What are the technical issues, user attitudes, and domain characteristics that may positively or adversely influence the adoption of additive manufacturing in the USMC?
    - Among 140 USMC and USN respondents, current adoption of AM is extremely low both at home and at work. In contrast to this low rate of adoption, the perceived potential of AM use is extremely high among all respondents.
    - Responses from surveyed participants confirm that leader endorsement and advertisement of technology capabilities are perceived as highly important factors in the adoption process.
    - Responses from surveyed participants confirm that perceived utility and ease of use of a new technology is an important aspect of the technology adoption process.

8.3 Recommendations for Future Work

Many avenues can be explored to realize full inclusion and adoption of AM in expeditionary operations. An overarching view of future work includes the following activities:

- Examine the use of Contour Crafting and CC for the construction of forward operating base shelters, HADR support, amphibious operations, and engineering obstacles. Structural integrity and ballistic testing will need to be conducted along with analysis of differing materials that can be used in Contour Crafting and CC.
- Design and develop discrete event simulations to determine the best and most efficient use of a diverse set of AM resources in expeditionary operations. Not all places will have or need all types of 3D printers. This simulation would allow study of an optimal solution based on projected needs and project the number and distribution of a diverse set of printers in a given segment of military user domain.
- Optimal use of the Digital Twin approach and its supporting system infrastructure with respect to USMC logistics operations and systems engineering.
- Longitudinal study that includes a repeated surveys of a larger number of users, including personnel from other services. The ultimate goal is to acquire better understanding about the adoption of new technology within the entire DOD.

The ultimate goal of using any new technology is to conduct ourselves in more efficient and effective ways, and to create new capabilities that would not exist otherwise.

To gain the most utility out of AM on a large scale, the USMC and USN must embrace the manufacturing paradigm shift. The paradigm shift does not center on what 3D printing can do, or what it may be able to print; rather, the paradigm shift focuses on what 3D printing and AM as a whole enables users to do now that its possible to turn things into data and, crucially, data into actual things. [21].

The USMC and USN must develop prototype repositories now. Materials technologies and AM mechanical technologies will continue to develop at a rapid pace. The U.S. maritime forces need to prepare for those operations by building and testing multiple iterations of draft 3D model repositories. Cyber-security will have to be woven into these repositories from the outset along with social capabilities that enable the open sharing of methods and techniques. The social capability is of greater importance in the outset of AM adoption

in the military domain so that Marines and sailors will not repeat the mistakes that others around the world have made while printing and modifying parts and pieces. Repositories will be not only stationary libraries, but a living, breathing, and learning rapid reaction forum.

It is highly conceivable that new and bigger challenges will be presented to the military in the operational domain. After all, they always have been. Inevitably, demand will increase for exploration of new ways of doing old tasks, a flexibility and ingenuity that can address new demands and conduct new tasks that have never existed before. A good example of a new way of dealing with future situations is reflected in the distributed logistics system that will fully support expeditionary manufacturing; the distributed logistics system approach will allow the military domain to maintain the adaptability and cunning speed that has defined USMC amphibious warfare throughout its history.

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APPENDIX A: Survey and IRB Approval Package

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Survey of USMC Combat Engineers and Navy Seabees and their Views on Technology

Naval Postgraduate School

Captain Matthew Friedell / USMC

Thank you for volunteering to take this survey. I am conducting research on new and emerging technology from Navy Seabees and USMC Combat Engineers. Throughout the survey, you will be asked a series of questions concerning your views and opinions about new and emerging technology such as 3D printing and virtual reality. This survey will not be used to evaluate you personally.

Thank you again for taking this survey. Please take the survey in one sitting.

There are 72 questions in this survey

Survey of USMC Combat Engineers and Navy Seabees and their Views on Technology

[]

Please read the following "Consent to Participate" prior to proceeding with the survey.

AUTHORITY: 10 U.S.C. 5013; 10 U.S.C. 5041; 10 U.S.C. 1074f; 32 CFR 64.4; DoD Instruction 1215.13; DoD Instruction 3001.02; CJCSM 3150.13C; DoD Instruction 6490.03; SECNAVINST 1770.3D; MCO 7220.50B; and E.O. 9397 (SSN), as amended.

Consent to Participate in Research

Introduction. You are invited to participate in a research study entitled " Study of Additive Manufacturing in United States Marine Corps and Navy Seabee Operations: Current and Future Needs, Technical and Domain Challenges and Opportunities.**" The purpose of this research study is to survey Marines and Sailors about various factors to determine which factors have the most significant impact on technology use and diffusion of innovation.**

Thank you for volunteering to take our survey.

Procedures. You are being asked to complete a web-based anonymous survey relating to the impact of technology use and diffusion of innovation. The survey should take approximately 10-15 minutes to complete, must be taken in one sitting, and can be taken during working hours. The expected number of participants who will have the opportunity to participate in this research study is approximately 500, all from the US Navy and USMC.

Location. The survey will take place online using LimeSurvey.

Cost. There is no cost to participate in this research study.

Voluntary Nature of the Study. Your participation in this study is strictly voluntary regardless of whether or not you are a bargaining union member. If you choose to participate, you can change your mind at any time and withdraw from the study. You will not be penalized in any way or lose any benefits to which you would otherwise be entitled if you choose not to participate in this study or to withdraw.

Potential Risks and Discomforts. The potential risk of breach of confidentiality is minimal in this study. This survey is anonymous and strictly voluntary. No IP addresses will be collected, and no personally identifiable information (PII) will be collected.

Anticipated Benefits. You will not directly benefit from your participation in this research. This research will benefit the Department of the Navy and the Department of Defense and may lead to increased awareness of the factors which influence well-being and point toward effective uses of resources for training and/or future use of technology.

Compensation for Participants. You will not receive any monetary/tangible compensation.

Confidentiality & Privacy Act. Any information that is obtained during this study will be kept confidential to the full extent permitted by law. All efforts, within reason, will be made to keep your personal information in your research record confidential, but total confidentiality cannot be guaranteed. All survey responses are anonymous and will not be shared with anyone outside the investigating research team. Once the participants submit their responses online, the information is immediately sent to LimeSurvey; therefore, the survey responses are not stored on their computers. Only the researcher and principal investigators will have access to the collected data for analysis. LimeSurvey online services host the survey questionnaire for collecting the data. The data will be stored in a secured database. The principal investigator will maintain all electronic data upon completion of the study for 10 years. Please

complete the survey in one sitting and ensure that you have a reasonable level of privacy as you take the survey.

Points of Contact. If you have any questions or comments about the research, or you experience an injury or have questions about any discomforts that you experience while taking part in this study, please contact the Principal Investigator, Dr. Amela Sadagic, (831)656-3819, asadagic@nps.edu. Questions about your rights as a research subject or any other concerns may be addressed to the Naval Postgraduate School IRB Chair, Dr. Larry Shattuck, 831-656-2473, lgshattu@nps.edu.

Statement of Consent. I have read the information provided above. I have been given the opportunity to ask questions, and all the questions have been answered to my satisfaction. I understand that by agreeing to participate in this research, I do not waive any of my legal rights.

I understand that my participation is strictly voluntary. If I decide to participate, I may choose to stop my participation at any point in the research, without fear of penalty or negative consequences of any kind. I can withdraw at any time by exiting the online survey.

I have read this consent form detailing the purpose and procedures for this research, and I am completing this online survey as evidence of my consent to be a participant in this research study.

By clicking on the "Yes" button, I am acknowledging that I have read and understand this information, and that I agree to voluntarily participate in the online survey.

Please either click the "Yes" button and proceed with the survey or exit the survey if you choose not to participate.
*****

Please choose **only one** of the following:

○ Yes

Frequently Asked Questions

What is the purpose of this study?

The purpose of this study is to gain a better understanding on the views and attitudes of Seabees and Marine Combat Engineers on new and emerging technology such as virtual reality and 3D printing.

Who can participate in this study?

Any active duty Navy Seabees and USMC Combat Engineers can participate in this study.

Demographics

[]Select Your Age *

Please choose **only one** of the following:

- 18-21
- 22-30
- 31-40
- 41-50
- 51 or over

[]How many years have you been in the military? *

Please choose **only one** of the following:

- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10
- 11
- 12
- 13
- 14
- 15
- 16
- 17
- 18
- 19
- 20
- 21
- 22
- 23
- 24
- 25
- 26
- 27
- 27+

[]Please select your gender *

Please choose **only one** of the following:

- Female
- Male

[]Input your MOS or Input *

Please write your answer(s) here:

MOS / Rating

[]Please select your rank *

Please choose **only one** of the following:

- E1
- E2
- E3
- E4
- E5
- E6
- E7
- E8
- E9
- WO1
- CWO2
- CWO3
- CWO4
- CWO5
- O1
- O2
- O3
- O4
- O5
- O6
- O6+

[]Select your highest education level *

Please choose **only one** of the following:

- High School Diploma or equivalent
- partial work towards Associates
- Associates Degree
- BS / BA
- partial work towards Masters
- Master's Degree
- partial work towards Doctorates
- PhD

3d Printing

[]I know what 3D printing is. *

	1: Strongly disagree	2: Disagree	3: Somewhat disagree	4: Neither disagree or agree	5: Somewhat agree	6: Agree	7: Strongly agree
Select one answer	○	○	○	○	○	○	○

[]I think that 3D printing has a great potential for home use. *

	1: Strongly disagree	2: Disagree	3: Somewhat disagree	4: Neither disagree or agree	5: Somewhat agree	6: Agree	7: Strongly agree
Select one answer	○	○	○	○	○	○	○

[]I think that 3D printing has a great potential for use in my work environment (military domain). *

	1: Strongly disagree	2: Disagree	3: Somewhat disagree	4: Neither disagree or agree	5: Somewhat agree	6: Agree	7: Strongly agree
Select one answer	○	○	○	○	○	○	○

[]I currently have and use some 3D printed items myself. *

Please choose **only one** of the following:

- ○ Yes
- ○ No

[]If 'Yes' Please explain what they are.

Please write your answer(s) here:

[]Our unit currently has and uses some 3D printed items. *

Please choose **only one** of the following:

- Yes
- No

[]If 'Yes' please explain what they are.

Please write your answer(s) here:

[]I think that a house could be 3D printed in the next 10 years. *

	Yes	No	I do not know
Select One	○	○	○

[]If given a 3D printing capability at my workplace I could use it immediately to make my workplace more efficient. *

	1: Strongly disagree	2: Disagree	3: Somewhat disagree	4: Neither disagree or agree	5: Somewhat agree	6: Agree	7: Strongly agree
Select one answer	○	○	○	○	○	○	○

[]To my knowledge my unit does have a 3D printing capability.

	Yes	No	I dont know
Select one answer	○	○	○

[]If Yes what are the printers being used for?

Please write your answer(s) here:

[]Given my knowledge of 3D printing, I believe that some parts used by our unit could be made (or invented) that way rather than carrying spare parts or purchasing new parts. *

	Yes	No	I dont know
Select one answer	○	○	○

[]What things or opportunities do you think 3D printing can be used for?

Please write your answer(s) here:

[]What problems do you see with respect to the idea of 3D printing?

Please write your answer(s) here:

[]I am aware that the Navy and USMC are both pursuing 3D printing technology *

	Yes	No
Select one answer	○	○

[]I think the USMC is quick to adopt new technologies. *

Please choose **only one** of the following:

- Yes
- No

[]I think the Navy is quick to adopt new technologies. *

Please choose **only one** of the following:

- Yes
- No

Other

[]Now I have a few questions about the future. Some books and movies portray a future where technology provides products and services that make life better for people. Others portray a future where technology causes environmental and social problems that make life worse for people. How about you? Over the long term, you think that technological changes will lead to a future where people's lives are mostly better or to a future where people's lives are mostly worse?

	Mostly Better	Mostly Worse	Don't Know	Refuse to Answer
Select one answer	○	○	○	○

[]Would you ride in a driverless car? *

	Yes	No	Don't Know	Refuse to Answer
Select one answer	○	○	○	○

Technology Use

Definition

Technology is defined as any computer (desktop/laptop), smart phone, tablet, 3D printer, smart glasses, game console; as well as software solutions like virtual training simulations, smartphone applications.

[]I am among the first ones who purchase and use examples of new technology when they become available. *

Please choose **only one** of the following:

- 1: Strongly disagree
- 2: Disagree
- 3: Somewhat disagree
- 4: Neither disagree or agree
- 5: Somewhat agree
- 6: Agree
- 7: Strongly agree

[]I always actively look for information about new technology that I could use. *

Please choose **only one** of the following:

- 1: Strongly disagree
- 2: Disagree
- 3: Somewhat disagree
- 4: Neither disagree or agree
- 5: Somewhat agree
- 6: Agree
- 7: Strongly agree

[]I always actively look for information about new technology that our unit could use. *

Please choose **only one** of the following:

- 1: Strongly disagree
- 2: Disagree
- 3: Somewhat disagree
- 4: Neither disagree or agree
- 5: Somewhat agree
- 6: Agree
- 7: Strongly agree

[]I keep myself well informed about current and future technologies that I could use *

Please choose **only one** of the following:

- 1: Strongly disagree
- 2: Disagree
- 3: Somewhat disagree
- 4: Neither disagree or agree
- 5: Somewhat agree
- 6: Agree
- 7: Strongly agree

[]I keep myself well informed about current and future technologies that our unit could use. *

Please choose **only one** of the following:

- 1: Strongly disagree
- 2: Disagree
- 3: Somewhat disagree
- 4: Neither disagree or agree
- 5: Somewhat agree
- 6: Agree
- 7: Strongly agree

[]I am among the last ones who buy and tryout examples of new technology. *

Please choose **only one** of the following:

- 1: Strongly disagree
- 2: Disagree
- 3: Somewhat disagree
- 4: Neither disagree or agree
- 5: Somewhat agree
- 6: Agree
- 7: Strongly agree

[]I like to wait to see if new technology catches on first before I buy it for myself. *

Please choose **only one** of the following:

- 1: Strongly disagree
- 2: Disagree
- 3: Somewhat disagree
- 4: Neither disagree or agree
- 5: Somewhat agree
- 6: Agree
- 7: Strongly agree

[]I am more likely to use a new technology if my peers recommend it to me. *

Please choose **only one** of the following:

- 1: Strongly disagree
- 2: Disagree
- 3: Somewhat disagree
- 4: Neither disagree or agree
- 5: Somewhat agree
- 6: Agree
- 7: Strongly agree

[]I am very likely to promote and advertise some technology among my peers outside of work. *

Please choose **only one** of the following:

- 1: Strongly disagree
- 2: Disagree
- 3: Somewhat disagree
- 4: Neither disagree or agree
- 5: Somewhat agree
- 6: Agree
- 7: Strongly agree

[]I am very likely to promote and advertise some technology that we could use at work. *

Please choose **only one** of the following:

- 1: Strongly disagree
- 2: Disagree
- 3: Somewhat disagree
- 4: Neither disagree or agree
- 5: Somewhat agree
- 6: Agree
- 7: Strongly agree

[]If my leadership uses some technology, <u>I am</u> more likely to try it myself. *

Please choose **only one** of the following:

- 1: Strongly disagree
- 2: Disagree
- 3: Somewhat disagree
- 4: Neither disagree or agree
- 5: Somewhat agree
- 6: Agree
- 7: Strongly agree

[]If my leadership endorses some technology that is not mandatory but it could be useful for our unit, I am more likely to try it. *

Please choose **only one** of the following:

- 1: Strongly disagree
- 2: Disagree
- 3: Somewhat disagree
- 4: Neither disagree or agree
- 5: Somewhat agree
- 6: Agree
- 7: Strongly agree

[]If our leaders endorse some technology that is not mandatory but it could be useful for our unit, <u>our unit</u> is more likely to use it. *

Please choose **only one** of the following:

- 1: Strongly disagree
- 2: Disagree
- 3: Somewhat disagree
- 4: Neither disagree or agree
- 5: Somewhat agree
- 6: Agree
- 7: Strongly agree

[]I am not likely to use new technology at work until it is mandatory. *

Please choose **only one** of the following:

- 1: Strongly disagree
- 2: Disagree
- 3: Somewhat disagree
- 4: Neither disagree or agree
- 5: Somewhat agree
- 6: Agree
- 7: Strongly agree

[]Our unit is not likely to use some technology until it is mandatory. *

Please choose **only one** of the following:

- 1: Strongly disagree
- 2: Disagree
- 3: Somewhat disagree
- 4: Neither disagree or agree
- 5: Somewhat agree
- 6: Agree
- 7: Strongly agree

[]I consider myself to be very efficient at using technology. Efficient is defined as performing a task more quickly and with better precision than an average person *

Please choose **only one** of the following:

- 1: Strongly disagree
- 2: Disagree
- 3: Somewhat disagree
- 4: Neither disagree or agree
- 5: Somewhat agree
- 6: Agree
- 7: Strongly agree

[]I have someone who helps me on a regular basis with technology that I use at work. *

Please choose **only one** of the following:

- 1: Strongly disagree
- 2: Disagree
- 3: Somewhat disagree
- 4: Neither disagree or agree
- 5: Somewhat agree
- 6: Agree
- 7: Strongly agree

[]I am responsible for recommending new technology in my unit. *

Please choose **only one** of the following:

- 1: Strongly disagree
- 2: Disagree
- 3: Somewhat disagree
- 4: Neither disagree or agree
- 5: Somewhat agree
- 6: Agree
- 7: Strongly agree

[]I am responsible for making final decision regarding the purchase of some new technology in our unit. *

Please choose **only one** of the following:

- Yes
- No

[]When compared to other units, our unit is among the first ones to acquire and use new technology *

Please choose **only one** of the following:

- 1: Strongly disagree
- 2: Disagree
- 3: Somewhat disagree
- 4: Neither disagree or agree
- 5: Somewhat agree
- 6: Agree
- 7: Strongly agree

[]My unit, on the whole, has a favorable attitude toward new technology. *

Please choose **only one** of the following:

- 1: Strongly disagree
- 2: Disagree
- 3: Somewhat disagree
- 4: Neither disagree or agree
- 5: Somewhat agree
- 6: Agree
- 7: Strongly agree

Technology Owned and Used

[]Estimate the average time you use a computer at home.

	Daily	Weekly	Monthly	Rarely	Do not use
Select one answer	○	○	○	○	○

[]Estimate the average time you use a computer at work.

	Daily	Weekly	Monthly	Rarely	Do not use
Select one answer	○	○	○	○	○

[]How many computers (both desktop and laptop) are in your household?

	0	1	2	3	4	5+
Select one answer	○	○	○	○	○	○

[]How many of those computers you use actively yourself?

	0	1	2	3	4	5+
Select one answer	○	○	○	○	○	○

[]How many smartphones are in your household?

	0	1	2	3	4	5+
Select one answer	○	○	○	○	○	○

[]How many of those smartphones you use actively yourself?

	0	1	2	3	4	5+
Select one answer	○	○	○	○	○	○

[]How long ago did you buy your first smartphone?

	1 year	2 years	3 years	4 years	5+ years
Select one answer	○	○	○	○	○

[]How many gaming consoles are in your household, working or not?

	0	1	2	3	4	5+
Select one answer	○	○	○	○	○	○

[]How many of those gaming consoles you use actively yourself?

	0	1	2	3	4	5+
Select one answer	○	○	○	○	○	○

[]Do you use the internet or email, at least occasionally?

	Yes	No
Select one answer	○	○

[]Do you access the internet on a cell phone, tablet or other mobile handheld device, at least occasionally?

Please choose **all** that apply:

- ☐ Cell Phone
- ☐ Tablet
- ☐ Other mobile handheld device

[]If you do have a smartphone, how often do you check your smartphone for updates hourly? (calls, messags or notifications)

	Less than once a day	About once per day	A few times per day	About once per hour	A few times per hour	Every few minutes
Select one answer	○	○	○	○	○	○

[]When faced with the choice of High Definition/Standard Definition video quality, which do you choose at home? Example: streaming video from specialized video-on-demand service like Netflix

	HD	SD	I do not watch video using on-demand services
Select one answer	○	○	○

[]When faced with the choice of High Definition/Standard Definition video quality, which do you choose on mobile? Example: streaming video from specialized video-on-demand service like Netflix

	HD	SD	I do not watch video using on demand services on mobile device
Select one answer	○	○	○

[]What are your frequently used applications/visited websites?"

Please choose **all** that apply:

- ☐ Facebook
- ☐ Twitter
- ☐ Snapchat
- ☐ Instagram
- ☐ Email
- ☐ Youtube
- ☐ News Sites (Fox News, CNN, MSNBC etc.)
- ☐ blogs

[]I prefer to read a hard copy of the newspapers rather than read digital version of the same information.

	1: Strongly disagree	2: Disagree	3: Somewhat disagree	4: Neither disagree or agree	5: Somewhat agree	6: Agree	7: Strongly agree	I do not read newspapers
Select one answer	○	○	○	○	○	○	○	○

[]I prefer to read a hard copy of the book rather than read digital version of the same book.

	1: Strongly disagree	2: Disagree	3: Somewhat disagree	4: Neither disagree or agree	5: Somewhat agree	6: Agree	7: Strongly agree
Select one answer	○	○	○	○	○	○	○

Technology Usage

[]Select all types of technology that apply to your regular daily activity _at home_.

Please choose **all** that apply:

- ☐ Computer
- ☐ Tablet
- ☐ Smart Watch or Fit bit
- ☐ Cell Phone
- ☐ Virtual Reality system
- ☐ 3D Printer

[]

Select all types of technology that apply to your regular daily activity at _your workplace_.

Please choose **all** that apply:

- ☐ Computer
- ☐ Tablet
- ☐ Smart Watch or Fit bit
- ☐ Cell Phone
- ☐ Virtual Reality system
- ☐ 3D Printer

[]If it takes more 15 minutes to learn a new technology, I give up on it and continue doing things the way I did prior to attempting the new technology Eg. Ordering a pizza via telephone or ordering pizza through an app.

	1: Strongly disagree	2: Disagree	3: Somewhat disagree	4: Neither disagree or agree	5: Somewhat agree	6: Agree	7: Strongly agree
Select one answer	○	○	○	○	○	○	○

[]How many new systems has your unit adopted and used in the past 3 years? [A system is defined as any combination of different types of technology used to increase the efficiency (productiveness) of you or any part of your unit.]

	0	1	2	3	4	5	6+
Select one answer	○	○	○	○	○	○	○

[]If your unit did adopt examples of new technology, what were those? Fill in.

Please write your answer(s) here:

1 per line

[]Approximately how many technological devices have you purchased in the last 3 years for your own personal use?

	1	2	3	4	5	6+
Select one answer	○	○	○	○	○	○

[]What were they?

Please choose **all** that apply:

- ☐ computer
- ☐ gaming system
- ☐ tablet
- ☐ smart phone
- ☐ smart watch, fitbit
- ☐ Virtual Reality system (A head mounted display system)
- ☐ 3D Printer

[]Approximately how many new software solutions (apps, games) did you install on your own smartphone during 2015?

	1	2	3	4	5	6	7	8	9	10
Select one answer	○	○	○	○	○	○	○	○	○	○

Submit your survey.
Thank you for completing this survey.

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APPENDIX B:
Basic History of Additive Manufacturing (AM)

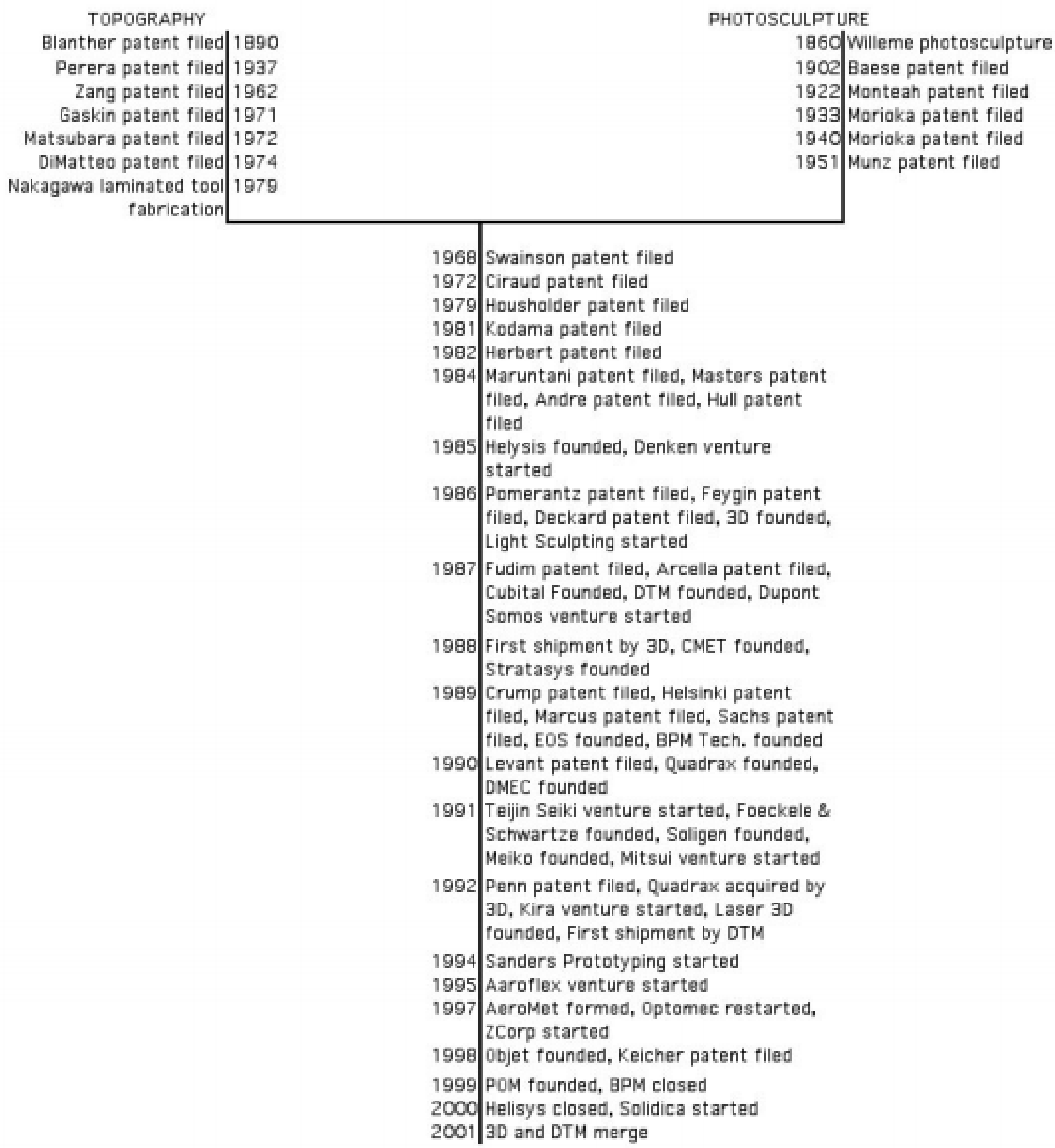

Figure B.1: Basic History of Additive Manufacturing. Source: [47]

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APPENDIX C: Response to Commandant of the Marine Corps Request for Information

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INFORMATION PAPER

3 Dec 2015

Subj: Response to Commandant of the Marine Corps (CMC) Request for Information (RFI) Regarding Additive Manufacturing (AM)

Encl: 1) Space and Naval Warfare Systems Command (SPAWAR) 3-D Shelters Overview

1. Purpose. To answer CMC's RFI regarding AM-produced parts in the Marine Corps inventory and the maturity of AM-produced shelters.

2. Key Points.
On 30 November 2015, the CMC inquired to Deputy Commandant, Installations & Logistics (DC, I&L) on two topics. DC, I&L's nascent innovation team, termed NexLog, has been assigned responsibility for answering these two inquiries. This non-traditional team is composed of members from I&L; Marine Corps Systems Command; Deputy Commandant, Combat Development & Integration; the Office of Naval Research; SPAWAR; the Naval Postgraduate School (NPS); and the Deputy Chief of Naval Operations, Logistics (OPNAV N4).

The first inquiry sought to discover the quantity of additively manufactured (3-D printed) Marine Corps parts that were either printed or purchased. To the knowledge of the NexLog AM team, there are no AM parts being printed or purchased for use in operational Marine Corps equipment. A 4 December tasker has been produced by SYSCOM in order to confirm this initial estimate and a follow-up will be provided if contrary information is discovered. However, there is a small set of niche uses of AM within the Marine Corps today. Many of those relate to AM in a tooling, prototyping, and remanufacturing role. The one exception to this is the production of parts for the MV-22 Osprey on behalf of a Naval Air Systems Command (NAVAIR) demonstration. The NexLog AM team is chartered to integrate these isolated experiments; initiate new experiments where needed, and develop a cohesive vision and strategy for future AM use in the Marine Corps.

The second inquiry sought to discover the status regarding AM-produced shelters for the purpose of habitability. This inquiry was chiefly answered through SPAWAR's 3-D Shelters Overview (Enclosure 1) and Marine Corps Captain Matt Friedell, an NPS student writing his thesis in this area. The NexLog AM team is currently not aware of any DoD initiatives focused on AM-produced structures.

The field of AM structures has been pioneered for over 20 years by University of Southern California professor Dr. Behrokh Khoshnevis. Dr. Khosnevis also owns a company known as Contour Crafting (CC), a well-known industry leader. It is important to note that the Chinese have allegedly copied Dr. Khosnevis' technology and have begun printing structures themselves[1]. CC is developing a machine that fits into a 20 foot container and can be assembled by four people in six hours. Once assembled, the machine is capable of printing 2,500 square feet in 20 hours. Future development will focus on "printing from above," whereby a skyscraper could be printed floor-by-floor, with the printer rising as each floor is printed. This technology could be easily

[1] http://3dprint.com/57764/winsun-3d-print-fake/

adapted for printing not only housing structures, but also base perimeters, blast walls, and many other potential applications. Additionally, ONR and the Army Research, Development, and Engineering Command (RDECOM) are actively looking to develop concrete from locally available and salvageable materials. When combined, this provides significant military advantage for the production of hardened structures across the range of military operations.

The NexLog AM team also adds that the CMC's interest in AM structures demonstrates the expansive future potential applications of AM outside the production of AM-manufactured parts. As the field of advanced manufacturing expands into digital textiles, flexible electronics, and AM materials that range from concrete to biological cells, the Marine Corps can expect a surplus of new and unpredictable applications. The challenge lies in adapting these applications for military use and then delivering them into the hands of the Marine in a timeline that provides tactical and strategic advantages over adversaries.

Prepared by: Capt Chris Wood, HQMC, I&L, LX/LPV, (571) 256-2740
Reviewed by: Col Nancy Springer, HQMC, I&L, LPV, (571) 256-7174

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